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An Evaluation of Coal Water Slurry Fuel Burners and Technology

by

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The U.S. Army has been tasked to reduce its dependence on and consumption of petroleum fuels. Coal water slurry fuel (CWSF) is considered a feasible alternative to the heavy fuel oil currently used as a boiler fuel. At the core of CWSF technology is the burner. Private enterprise has invested heavily in burner development with the objective of achieving a design that performs as well as conventional pulverized coal burners.

This study evaluates industrial research and development efforts on CWSF technology and burners to identify the burner systems most promising for Army CWSF conversions. Burner performance targets developed for the Electric Power Research Institute (EPRI) were compared to performance data reported by burner manufacturers. This evaluation found that although burners manufactured by the Babcock & Wilcox Company (B&W) and Combustion Engineering, Inc. (CE) most closely meet the performance targets, testing was conducted under ideal conditions. Performance data indicated that these burners should receive additional consideration and laboratory testing for use in the Army's central heat plants and package fire-tube boilers.

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FOREWORD

This study was done for the U.S. Army Engineering and Housing Support Center (USAEHSC). The work was done under Project 4A62784AT45, "Energy and Energy Conservation"; Work Unit D006, "Coal Use Technologies." The Technical Monitor is Bernard S. Wasserman, CEHSC-FU.

This work was completed by the Pennsylvania State University Fuel Science Program Combustion Laboratory under contract to the Energy and Utility Systems Division (FE), Infrastructure Laboratory (FL), U.S. Army Engineering Research Laboratories (USACERL). Dr. David Joncich is Chief, CECER-FE and Dr. Michael O'Connor is Chief, CECER-FL. The principal investigators were Prakash Ramachandran and Ching-Yi Tsai. Gary W. Schanche was USACERL's Project Manager.

COL Daniel Waldo, Jr., is Commander and Director of USACERL and Dr. L.R. Shaffer is Technical Director.

EXECUTIVE SUMMARY

The U.S. Army has been tasked to reduce its dependence on and consumption of petroluem fuels. Coal water slurry fuel (CWSF) is considered a feasible alternative to the heavy fuel oil currently used as a boiler fuel. At the core of CWSF technology is the burner, which is a hybrid between a pulverized coal burner and a No. 6 fuel oil burner. Private enterprise has invested heavily in burner development with the objective of achieving a design that performs as well as conventional pulverized coal burners.

This study evaluates industrial research and development efforts on CWSF technology, particularly burner technology, to identify the burner systems most promising for Army CWSF conversions. Performance targets developed for the Electric Power Research Institute (EPRI) were compared with burner performance data reported by the manufacturers. This evaluation found that burners manufactured by the Babcock & Wilcox Company (B&W) and Combustion Engineering Inc. (CE) should receive additional consideration and laboratory testing for use in the Army's central heating plants and package fire-tube boilers.

Objective comparisons between burners are not available; there are no reports of side-by-side tests of commercial burners conducted by a third party using the same test furnace or boiler, operating conditions, and fuel. The performance data were reported by the manufacturers. Coals were usually of high volatile matter (VM) content (for ignition stability and turndown), with low sulfur, nitrogen, and ash contents (the ash usually had innocuous properties because of high fusion temperature and low abrasivity), and good slurryability. Slurries generally had a high percentage of coal (or high solids loadings, to minimize moisture-related ignition problems and boiler efficiency losses), while maintaining an acceptably low value for high shear viscosity for efficient atomization. Test conditions minimized slagging/fouling to ensure complete burnout (i.e., the tests used a liberally-sized combustor with a low rate of heat absorption). More refractory surface than is common in practical boilers was sometimes used to enhance flame stability and reduce the need for support fuel firing and extensive combustion air preheating. Atomization was sometimes effected using high pressures for atomizing media and/or fuel and high ratios of atomizing media to fuel mass flow rate. In practice, such energy-expensive methods can mean a prohibitively high operating cost.

The two companies that have been recommended have considerable experience in various important aspects of CWSF technology. Both work with slurry fuel producers and can offer potential users an entire range of services, from fuel production, delivery, and handling systems to economic studies, boiler conversions, and new burners. Both companies have conducted research programs under the auspices of EPRI. CE has carried out a multifaceted CWSF research project under the sponsorship of the Department of Energy (DOE). CE has demonstrated the feasibility of two burner designs, one for wall firing applications and the other for tangential (corner) firing boilers, in field testing outside their own facilities. CE also has expertise in studies on conversion feasibility and economics. B&W's burners in a variety of sizes have been proven during testing outside their own facilities. The B&W burner has tri-fuel capability (CWSF, oil, or natural gas) without requiring physical replacement of any part of the burner, which is convenient when a conventional fuel must be fired to attain peak loads that cannot be achieved on CWSF alone, due to derating. Because of the infancy of CWSF technology, cautiousness on the part of the corporations has meant that tests and demonstrations conducted thus far have been in liberally-sized combustors and not in the units of greater consequence—compact boilers designed for oil-firing that have no capability of, or provisions for, burning coal and coal-based fuels.

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1 INTRODUCTION

Background

The U.S. Army has been tasked to reduce its dependence on and consumption of petroleum fuels; hence the Corps of Engineers is investigating alternate energy technologies and conversions to noncritical fuels. About 48 percent of the Army's petroleum is consumed in boiler plants at its base facilities (44 million barrels per year [bbl/yr] in 1983) and these appear at least partly amenable to conversion to firing of other fuels. Coal water slurry fuel (CWSF) represents a feasible method for burning coal in boilers designed for oil and natural gas.

However, oil- or gas-fired boilers at Army plants cannot be converted to burn CWSF unless the fuel burner is redesigned. This evaluation of test and prototype burners can help Army engineers design Army CWSF conversions. Overall, the Army is targeting both large, watertube boilers in central heating plants as well as smaller, package fire-tube boilers for future CWSF retrofit (1, 2).*

Objective

This research provides an overview of ongoing industrial and governmental research and development efforts on CWSF technology and burner systems to identify the burner systems most promising for Army CWSF conversions.

Approach

The initial step in the project was to compile a list of CWSF burner manufacturers. The November 1985 buyers' guide edition of *Power* magazine (McGraw-Hill) lists the following slurry fuel, including fuels other than CWSF, burner manufacturers in the United States and abroad:

- Babcock & Wilcox Co., Power Generation Group, Barberton, OH
- Babcock & Wilcox Canada; Babcock & Wilcox International Division, Cambridge, Ontario, Canada
- Babcock Power Ltd., London, England
- Coen Co., Burlingame, CA
- Foster Wheeler Energy Corp., Livingston, NJ
- Ishikawajima-Harima Heavy Industry Co. Ltd. Basic Design Dept., Boiler Plant Div., Koto-ku, Tokyo, Japan
- Keeler/Dorr-Oliver Boiler Co., Williamsport, PA
- NEI International Combustion Ltd., Derby, England

* References are listed by chapter at the end of the text starting on p 92.

- Peabody Engineering, Stamford, CT
- Preferred Utilities Manufacturing Corp.
- WN Best Combustion Equipment Inc., Danbury, CT
- John Zink Co., Tulsa, OK

Through contacts with CWSF manufacturers, two omissions in this list were found:

- Combustion Engineering, Inc., C-E Power Systems, Windsor, CT
- Parker-Hannifin Corp., Gas Turbine Fuel Systems Div., Cleveland, OH.

Researchers identified other manufacturers in the available literature. Requests for information regarding their burners and the reason it was sought were sent to the prospective suppliers. Of those who responded, some had experience with slurry fuels but not specifically with CWSF and were not included in this study. Contacts were also developed during the Fifth International Workshop on Coal-Liquid Fuels Technology held October 15-18 1985, at Halifax, Nova Scotia, Canada and at the Eighth International Symposium on Coal Slurry Fuels Preparation and Utilization held May 27-30 1986, at Orlando, FL. Researchers gained first-hand knowledge by witnessing a demonstration burn of CWSF at the Babcock & Wilcox Co (B&W) NED Manufacturing facility in Barberton, OH, in March 1986, and by visiting the Foster Wheeler and Carbogel plants in Livingston, NJ. In addition to the internal papers, company reports, brochures describing equipment and fuels, and press releases that were provided by companies, research papers from three different international symposia on coal-liquid mixtures were used during this evaluation. Open literature, particularly proceedings of these and other symposia, Electric Power Research Institute (EPRI) reports, as well as papers published in relevant journals, provided the bulk of the information obtained. The literature review, though not exhaustive, covers the major fuel and burner development efforts of the various corporations. EPRI performance targets that are commonly used to rate liquid fuel burners were compared to performance data of the research and prototype burners. A recommendation for additional consideration and laboratory testing of the burners manufactured by two companies is included.

Scope

The information in this report is intended to serve as a reference covering state-of-the-art CWSF burner systems that might be employed in the Army's natural gas and fuel oil boilers. It is intended for engineers evaluating or designing a plant for conversion and assumes that the reader understands fuel oil combustion and is somewhat familiar with pulverized coal combustion.

Mode of Technology Transfer

It is recommended that the information contained in this report be summarized in a Technical Note covering coal combustion retrofit technologies.

2 USE OF CWSF IN COMPACT BOILERS

Since the energy crises of 1973 and 1979, oil-importing nations have become aware of their vulnerability to embargoes and escalating prices and have taken steps to lessen their dependence on petroleum. CWSFs are expected to offer one alternative to imported oil. CWSFs are thick, black, syrupy liquids with the consistency of latex paint. In their most common "highly loaded" form they are composed of 70 to 75 percent (by weight) highly volatile bituminous coal, 24 to 29 percent water and 1 percent chemical additives. The principal potential market for CWSF is as a replacement for fuel oil in utility and industrial boilers (1), but potential applications being studied in the laboratory include the following:

- Gas turbines and large, slow diesel engines for electricity/heat cogeneration (the fuel must be of the ultrabeneficiated type)
- Fluidized bed combustion, coal gasification feedstock
- Blast furnace injection
- Pulsed combustion engines
- Diesel locomotives and retrofitted steam locomotives (in China).

Advantages of CWSF

As a liquid, CWSF has inherent advantages over solid coal. It may be stored in tanks, transported by a variety of methods, including pipelines, and pumped, atomized, and burned much like a heavy fuel oil (2). Unlike pulverized coal, there is no dust explosion hazard, no space is required for coal storage piles or pulverizers, which are also expensive to purchase and operate (3, 4). Other advantages include independence from foreign suppliers, assured future supply at a predictable price, relatively low cost compared to alternative synthetic fuels, and the fact that the technology is available (1, 4, 5). Since slurry manufacture involves fine milling of coal, it is compatible with beneficiation (treatment) processes, such as froth flotation, which reduce ash and pyritic sulphur content (4). Unlike pulverized coal, there is no need for expensive drying of the cleaned coal.

Recently, limestone has been added to slurries to capture sulfur oxides during the combustion process and reduce emissions (6). Due to the high moisture content of CWSF, flame temperatures are considerably lower than in pulverized coal flames. This results in lower nitrogen oxide emissions (5). However, since coals usually contain more fuel nitrogen than fuel oils, CWSF's nitrogen oxide emissions are correspondingly higher (7) than for fuel oil.

Production Methods

CWSF is being manufactured by many producers using proprietary processes. However, all share certain basic steps. The coal is crushed and mixed with water and wetting agents, then milled less than 300 microns (the mass median diameter or "mmd" is typically 30 to 50 microns) and beneficiated to remove ash. After being dewatered, flow and stability improvers are added to yield the final product (2). Dispersants (surfactants, such as calcium lignosulphonate) help to wet and separate individual coal particles and reduce the slurry viscosity, while stabilizers prevent the particles from settling into a hard-packed bed by suspending them in a weak gel. Stabilizers are generally starches, gums, salts, or clays (8). Other additives include freezing point depressants, biocides, and caustics (to control the pH of the product).

Combustion Methods and Equipment

The methods of burning CWSF in boilers resemble those used in both oil and pulverized coal firing. As with other liquid fuels, it is important that the fuel be as finely atomized as possible to maximize the surface area exposed to ignition heat sources and to minimize droplet volumes for rapid burnout. As with heavy fuel oil atomization, pressure-atomization is inadequate, so atomizers using either compressed air or high pressure steam are used. Due to the erosive nature of the slurry, internal-mixing type atomizers, the most common being Y-jet and T-jet designs, are made with wear-resistant materials. In high-shear areas within the burners, inserts made of tungsten carbide or ceramic materials are used. Manufacturers of external-mix atomizers have attempted to avoid the need for these costly inserts to prolong atomizer life by designing atomizers where the high-shear regions of fluid confluence are outside the atomizer. However, atomization quality is somewhat compromised in such designs. Another goal of manufacturers is to design an atomizer that gives a very fine spray without consuming too much of the atomizing media, thus limiting the expense for that media.

Despite recent progress in atomizer design, an "ideal" design which divides a slurry stream into individual coal particles has not been achieved. The coal particles in a slurry droplet tend to agglomerate, as discussed later in this chapter, and ultrafine grinding of coal does not alleviate the problem. One way to remedy this situation is to concentrate on the slurry rather than the atomizer. Secondary atomization techniques for disintegrating slurry droplets subsequent to or simultaneously with shear atomization appear to reduce the droplet size, but at increased cost. Some of the methods are superheating the slurry feed under pressure, dissolving pressurized carbon dioxide into the CWSF, or adding labile compounds such as picric acid to the slurry to cause microexplosions when the slurry is heated (9).

Changing the burner is the most important aspect of retrofitting oil-fired boilers to fire CWSF, but the greatest retrofit expense is related to the fact that coal combustion liberates much more ash than does oil firing. Modifications include making the furnace hopper bottom steeper to facilitate bottom ash removal; installing deslaggers for the furnace walls, soot blowers in the convection passes, ash handling equipment, mechanisms for removing fly ash from flue gases, such as electrostatic precipitators, bag filters, cyclones, etc.; replacing the economizer, if it is the finned-tube type with close spacings that could become plugged with fly ash, and possibly changing the tube spacing in the convection pass, as discussed later in this section (2, 3, 15). Depending on the coal used and the U.S. Environmental Protection Agency (USEPA) regulations governing the use of slurry, flue gas desulfurization may be required—a potentially large expenditure.

Combustion Process

The basic combustion properties of CWSF are more like those of pulverized coal (PC) than those of fuel oil. Due to the slowness of the heterogeneous char (solid carbon particle) combustion stage of coal combustion, the fuel burns much more slowly than oil. Since the char is a smaller "fraction" of oil (10) than of coal, oil has a much shorter char combustion time. As with PC particles, slurry droplets need a long residence time, i.e., a large combustion volume and high excess air levels for complete combustion. Burner designs for the newer fuel borrow heavily from those used for PC firing.

Once introduced into a furnace, CWSF droplets must be dried and brought to the ignition temperature as quickly as possible to ensure burnout within the residence time available. The heat needed is supplied largely by hot combustion gases brought into contact with the fuel/air mixture as the result of strong internal and external recirculation patterns in front of the burner (11, 12). These air patterns are created by air swirl vanes (see Figure 1) within the burner windbox. The vanes spin the air, thus imparting centrifugal force to it and forcing it at high velocity into the boiler. The centrifugal force results in a low air pressure zone immediately ahead of the burner nozzle for some distance. This low pressure zone draws combustion gases toward the burner, creating more turbulence and improving the combustion. Thus, internal and central recirculation of hot gases is set up, which aids in drying the slurry moisture, devolatilizing the coal, and heating the volatile matter evolved to ignition. External recirculation has a lesser but similar effect. Another source of heat to the unignited fuel spray is radiative heat transfer from the flame, and, to a smaller extent, nonluminous radiation from a portion of the combustion gases. Most commercial burner manufacturers go a step further in this respect by incorporating specially-shaped, refractory-lined divergent throats ("quarls") in their burner designs (13) (see Figure 2). The refractory absorbs heat from the surrounding gases and the flame and reradiates it to the nozzle. As in the case of PC, the secondary combustion air (that which is introduced at the windbox) needs to be preheated to 120 to 200 °C*. This serves to speed up drying of the slurry droplets. An alternative to preheating is cofiring with natural gas or oil as the support fuel, supplying 3 to 4 percent of the total heat generated.

Once a slurry droplet has been dried and devolatilized and the volatile matter burned, the remaining char burns heterogeneously with oxygen diffusing into the particle to enable combustion (14). The combustion air swirl now violently mixes the char with the combustion air (the particle follows a helical path in the "tornado" as depicted in Figure 1), maintaining a high oxygen gradient and forcing many of the smaller particles into at least partial normal combustion reactions. The result is faster char burnout. With particles entrained in the vortex, the residence time available for combustion is lengthened as well.

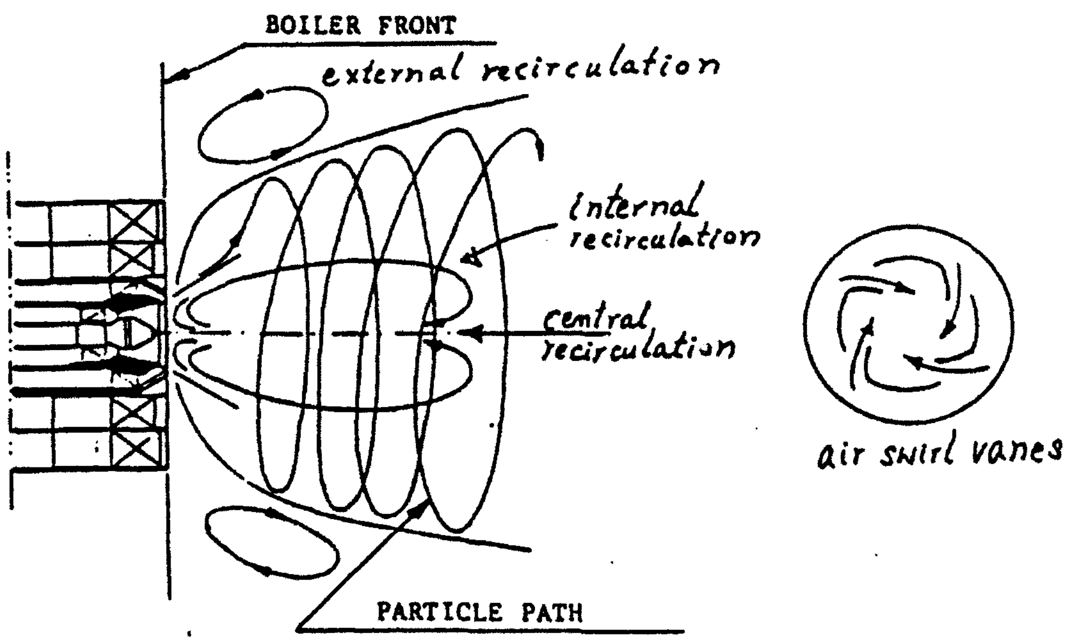


Figure 1. Recirculation of gases in the flame.

* A metric conversion table is provided on page 91.

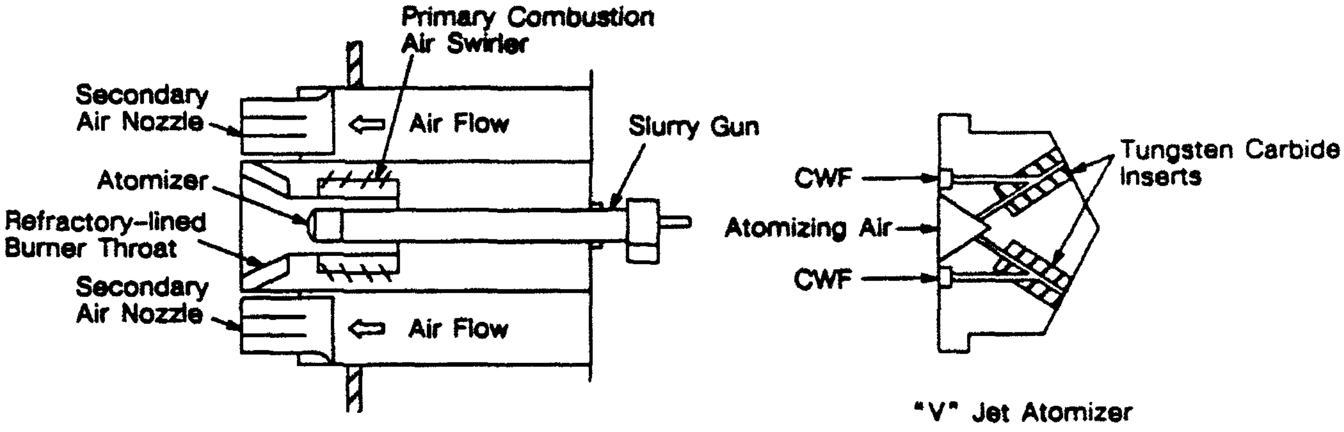


Figure 2. Burner for tangential firing.

The stages involved in the combustion of a coal water slurry droplet are very similar to those for dry pulverized coal. Upon atomization, droplets of slurry are formed, each consisting of many coal particles. The droplet's volume median diameter (vmd) is about four to six times larger than that of unslurried finely-ground coal (16). The top size of a droplet is two to three times larger than ground coal. The largest particles are the last to burn out, thus the burnout time is four to eight times longer for the slurry droplets than for unslurried finely-ground coal. It is therefore evident that atomizers presently available are far from perfected. In the furnace the droplet is heated by convection and radiation, the surface water dries and the coal particles agglomerate weakly due to surface forces. If the coal is of the caking variety, further heating leads to plastic deformation, melting, and fusion to form a mass of the same size as the original droplet. Devolatilization produces swelling and the volatile matter released ignites when its ignition temperature is reached. The high water content of CWSF delays ignition since it takes time to evaporate the water before devolatilization, and since water vapor acts as a diluent which reduces the flammability of the volatile matter and lengthens burning time. In addition, the flame temperature is lower for CWSF due to the energy absorbed by evaporation of the water. It takes approximately twice as long to ignite a slurry droplet as it does a coal particle of the same diameter, and in that time the droplet has moved 50 percent farther away from the burner, i.e., closer to the furnace exit (12, 17). The burnout distance for the entire droplet is typically twice that for a coal particle of equal diameter. For thermoplastic coals, swelling occurs simultaneously with devolatilization and evaporation of water from the drop core. CWSF made with lignite coal produces drops that show no swelling. The char of the former is cenospheric (a hollow sphere) and burns from the inside at a constant diameter while that of the latter burns as a shrinking sphere. Due to their larger diameter, the cenospheres burn more slowly and yield larger fly ash particles. Homogeneous combustion occurs on an atomic level, similar to gasoline and heterogeneous combustion occurs on a solid level, similar to charcoal. The combustion time of coal char is known to be roughly proportional to the square of the char diameter (12, 18). There are two coal properties related to diameter that are detrimental to satisfactory combusion of the char: agglomeration and swelling. Agglomeration is the sticking together of putty-like coal particles to make bigger particles. Swelling is the tendency of a coal particle to get larger as it is heated. Both of these properties increase the burnout time, and reduce the efficiency of carbon conversion given the limited residence time.

As discussed above, the presence of 30 percent by weight water in CWSF is partly responsible for a long ignition delay and a longer overall combustion time than for pulverized coal under the same conditions. However, in terms of a thermal penalty incurred by having to vaporize the water, the loss is significant but not prohibitive. For a 10,600 British thermal units per pound (Btu/lb) CWSF with 30 percent moisture, it is calculated that only 3 percent of the coal's calorific value is used to vaporize the water and heat it to the temperature of the combustion air leaving the air preheater (1).

Boiler Derating

One of the major obstacles to the widespread conversion of oil-fired boilers to fire CWSF is the fact that such boilers cannot produce as much steam with the new fuel as they do with oil. That is, they would have to be substantially "derated" when burning CWSF. There are three primary reasons why CWSF requires this derating: it needs a longer residence time for acceptable combustion, it produces more fly ash, and it has a lower ash fusion temperature.

It has been mentioned above that the largely homogeneous combustion of fuel oil is a rapid process compared to the largely heterogeneous combustion of coal. Hence, the fuel oil needs a substantially shorter residence time for combustion and thus a smaller combustor volume than coal does at the same firing rate. Firing coal in an oil-designed boiler at the rated capacity would result in an unacceptably low carbon burnout, which would be aggravated by the higher excess air levels coal firing demands compared to oil and natural gas. Firing CWSF would result in even higher carbon losses due to the ignition delay, agglomeration, increased flow of gas through the furnace, because of the evaporated water, and the correspondingly lower residence time available. The only solution, then, is to fire at a lower rate and produce less steam. Oxygen enrichment of the combustion air is one way of reducing the extent of derating.

Derating is also related to erosive fly ash because CWSF contains a great amount of ash. Heavy fuel oil contains very little ash, compared to coal. Consequently, the tubes in the convection pass of a steam generator are closely spaced and the gas velocity through the pass is high (up to 120 ft/s [15]) since there is no risk of erosion by fly ash. On the other hand, coal-fired boilers typically have flue gas velocities of 50 to 70 ft/s and the tube spacings in the convection pass are wider than in oil-fired units. Therefore, to reduce the amount of erosion when converting to CWSF, it is necessary to decrease the volume of flue gas which will reduce velocities in the convective section of the boiler. When firing CWSF in an oil-designed boiler, substantial derating must be expected. Mitigating steps include ultrafine grinding to minimize fly ash size, cofiring with a support fuel, beneficiation to remove part of the ash, using coals with ash having low abrasiveness, and removing some tubes in the convection pass. Because it is impossible to remove all the ash in a coal, derating cannot be circumvented completely (9).

It is common practice to size the furnace, the radiative heat transfer section of the boiler, so that enough heat is extracted from the flue gas to lower its temperature to below the ash fusion temperature. Thus, the fly ash is not sticky when it enters the convection zone and fouling is minimized. Oil has a lower ash content and a higher ash fusion temperature than coal. The higher fusion temperature means the furnace exit gas temperature (FEGT) can be higher for oil, with less risk of fouling the convection bank with sticky fly ash. Therefore, an oil-fired furnace can be smaller, i.e., heat absorption in this zone can be less than a coal-fired one for the same overall boiler rating. If coal or CWSF is fired in a small oil furnace that cannot lower the FEGT sufficiently, convection pass fouling can be severe. Slagging and fouling can be termed "autodegenerative" since both result in reduced heat transfer efficiency, which raises the furnace temperature and the FEGT, which in turn, exacerbate slagging and fouling, and so on. Therefore, derating is the only complete solution to the problem of an excessive FEGT, although using coals containing ash with a high fusion point may mitigate fouling.

Of these three major causes of derating, any one may be controlling. That is, the percentage of derating imposed by each phenomenon is not additive. If, for example, the residence time limitation dictates a derating of 20 percent, the erosion limitation 30 percent, and the FEGT limitation 25 percent, the overall derating is 30 percent. The boiler may operate at only 70 percent of oil-rated capacity using CWSF. Derating does not automatically mean that a retrofit to CWSF is not practical. If the peak load range of steam production is unavailable after the derating, but is still needed after conversion, two options are available: (1) the boiler can be fired on oil alone at peak load, which implies a high oil consumption rate, or (2) in addition to firing CWSF at the maximum rate dictated by the derating, a small auxiliary gas turbine unit may be used to supply additional power at the higher loads, implying a much lower rate of oil consumption but a significant capital expense for the turbine. Economic factors will decide the choice.

Ash Deposition

CWSFs are expected to exhibit ash deposition characteristics different from those of pulverized coal. This is because the greater water content of CWSF will cool the flame and keep the ash from agglomerating. CWSF also produces larger fly ash particles which do not pass through the boiler as those of pulverized coal (17). During storage of CWSF there is a possibility of alkali salts being leached from the coal by the slurry water, thus increasing the amount of alkali species vaporized during combustion. On the other hand, CWSF flames are cooler than pulverized coal flames and this tends to reduce the amount of volatile ash species being vaporized. It is difficult to gauge the overall impact of these opposing effects. The volatile ash species exist as a liquid on the cooled furnace heat transfer surfaces, creating a sticky layer that catches fly ash particles. More than two-thirds of fly ash particles are larger than 10 microns and when they are in a moving gas stream, they are controlled by inertial forces, due to their larger mass, rather than by drag forces. When there is a curvature in the flow of the stream around a tube, the heavier particles are unable to follow the streamlines, hit the tube surface and are deposited there. The formation of slag deposits follows this sequential capture of the fly ash. The initial layer is rich in alkali salts from vapor condensation. Particles from 0.1 to 5 microns are captured by the sticky layer and the deposit grows. This layer is insulating and the temperature within the boiler rises. The trapped micron-size fly ash particles sinter (become tacky and stick together) and a liquid layer of molten slag appears. This sticky layer can now trap larger particles by inertial impaction. As previously discussed, fly ash from CWSF combustion is larger than that from PC combustion and contains much unburned carbon in incompletely combusted char cenospheres. The iron content of eastern U.S. coals lowers the melting point of other minerals present in ash, especially under reducing conditions such as those provided by captured unburnt carbon. Ash deposition is therefore expected to be worse with CWSFs than with PC firing.

Economic Factors

In late 1985, the price of CWSF was estimated to be $2.80 to 3.50/MBtu, depending on the costs of the coal, transportation from mine to preparation plant and then to customer, chemical additives, and processing, and on the extent of beneficiation. The price of residual fuel oil at the time varied between $4.60/MBtu and $5.60/MBtu (19). The cost differential between the two fuels was enough to pay, over a period of time, for retrofitting some existing oil-design boilers to fire CWSF, with some derating. By mid-1986, the price of oil had declined dramatically and the price differential between the two fuels had vanished. Consequently, there was little interest in converting boilers to fire CWSF and the industry is still in a period of dormancy (20), awaiting the inevitable upswing in the cost of petroleum. Although CWSF technology has advanced tremendously during the early 1980's, the soft oil market and the inherent nature of coal combustion, viewed as dirty, complex, and requiring highly trained people, combine to render it unattractive at present in the retrofit market.

3 BURNER EVALUATION CRITERIA

Based on test results alone, a CWSF burner cannot be evaluated for inherent performance characteristics. The burner's apparent performance is to a large extent affected by fuel properties: how easily fuel is atomized, the percent of volatile matter (VM) in the fuel, calorific value of VM, char reactivity, moisture content, low nitrogen content to suppress NOx emission, etc. However, even when using a premium fuel under optimum conditions, the performance of a burner is greatly affected by its design. These are some factors that affect performance:

- Liberally-sized combustors have adequate residence time for slow-burning fuels
- Temperatures in the primary combustion zone may be kept high by using a large area of refractory or extended refractory quarl or precombustion chamber
- Large combustors, because they have a low ratio of heat-absorbing surface to combustion volume, have a low rate of heat absorption. The hotter environment also accelerates the rate of combustion and improves flame stability—the addition of refractory panels further lowers heat absorption
- Wide furnaces provide more width for short, intense, stable, and generally more efficient flames than narrow funaces.

The performance criteria by which burners were evaluated in this report are summarized by EPRI's performance targets listed below for large, commercial CWSF burners:

- High turndown (at least 3:1) to be able to achieve low loads without firing support fuel
- Adequate nozzle life (at least 2000 h) to minimize maintenance
- Low excess air requirement (similar to that used in PC firing—about 20 percent) to minimize loss in boiler efficiency and to maximize residence time for combustion
- Low combustion air preheat levels (again typical of PC practice; EPRI's target of 300 °F or below is demanding) to limit preheating costs
- Low burner draft loss (burner pressure drop, windbox to furnace pressure drop) to allow use of existing blowers during retrofit (EPRI requires losses below 8 inches in water column)
- Fine fuel atomization (spray quality is possibly more critical to efficient fuel burnout than any other factor); EPRI specifies a target of no fuel droplets larger than 300 microns
- Flexibility in using either air or steam as the atomizing medium
- An atomizing medium to fuel mass flow rate (A/F) as low as possible to limit consumption of the pressurized medium—a cost penalty; EPRI specifies a ceiling of 0.15 on the A/F
- Ability to switch back and forth between No. 6 oil and CWSF to allow firing on oil to attain peak capacity if the unit is derated on CWSF, and to switch from one to the other in case of supply disruptions; evidently there is an added benefit in being able to efficiently atomize both fuels using the same nozzle, rather than having to manually switch nozzles—an increase in operator responsibility
- A commercially acceptable level of carbon burnout (EPRI requires greater than 99 percent) is of the greatest importance.

Though not specified by EPRI, it is evident that using fuel and atomizing medium streams at as low a pressure as possible, e.g., below 100 pounds per square inch gauge (psig), is convenient. It is also preferable that neither stream require preheating to avoid the associated, though minor, cost.

4 BABCOCK & WILCOX CO

Co-Al CWSF

The earliest B&W participation in CWSF technology development dates back to 1961, when about 12,000 tons of slurry with a solids loading of 62 to 68 percent were burned in a unit operated by Jersey Central Power & Light Co. (1). Their next involvement was more than 10 years later, as part of a consortium supporting the development of Co-Al (product name) fuel. Research initiated on CWSF in the late 1970s by Professor J. Funk of Alfred University, Alfred, NY, led to the Co-Al technology. Slurrytech, Inc., bought the exclusive license to marketing and development rights from the Alfred University Research Foundation, which holds the patent on Co-Al (1, 2, 3). Slurrytech then organized a development consortium whose primary financial contributors were B&W, Elf Technologies, Inc. (a subsidiary of Elf Aquitaine of France), the F-Coal Group, and Babcock Power Engineering Ltd. of the United Kingdom. The F-Coal Group is a group of Japanese companies headed by Marubeni Corp. and includes Babcock-Hitachi, Ltd.; Nippon Kokan, K-K; and Nippon Oil and Fats Co., Ltd. B&W has a worldwide license from Slurrytech to use the technology.

Co-Al fuel is stable and pumpable at relatively high solids loading (75 to 78 percent) (4, 5, 6). It can be stored for months with negligible settling, and freeze/thaw cycles do not affect its stability. The pressure drop for Co-Al flowing in a pipe is similar to that for a heated coal oil mixture (COM) or for oils heavier than No. 6 oil (5).

In 1980, B&W fired Co-Al without support fuel for the first time at their Alliance Research Center (1, 2, 3, 4, 5, 6). The slurry was preheated to 235 °F and the combustion air to 500 and 700 °F; the higher temperature was needed for stable ignition of coal with low volatile matter. Although carbon conversion was similar to that for PC in the same furnace, atomizer wear was significant. Sprayer plates constructed of carbon steel, stainless steel, and hardened tool steel showed extensive wear after 3 to 4 hours of operation.

In February 1982, Slurrytech started production at a continuous 50-ton/d Co-Al pilot plant at the KVS (Kennedy Van Saun Corp.) facility in Danville, PA (1, 2, 7), which has produced over 1500 tons for testing. The process is centered around a 6 by 11 ft ball mill. The highly loaded slurry has an advantage over other available slurries since a 10 percent savings in transportation costs can be realized by shipping at 77 percent solids rather than at 70 percent. The user may wish to dilute the slurry upon receipt to 73 to 76 percent to reduce its viscosity and improve atomization quality.

Co-Al from the KVS plant was shipped to Babcock-Hitachi in Japan where it was burned in a 40 MBtu/h burner. The atomizer was a steam-assisted internal mixing type and stable combustion was attained without the use of a support fuel (6, 8). Combustion air needed to be preheated to 300 °C and it was beneficial to preheat the slurry to 70 °C. Combustion efficiency was about 99 percent, the same as that noted when PC from the same coal was burned. NOx emissions were 150 to 250 parts per million (ppm), 100 ppm lower than for the PC.

Babcock Power in the United Kingdom also has performed testing on Co-Al and is developing a CWSF burner specifically for Co-Al applications. The unique design consists of a cyclone into which CWSF is sprayed and dried by contact with hot, swirling air, before being expelled into the boiler and burned (6, 9). Two 60,000 lb/h boilers are being converted to fire CWSF in Scotland.

In October 1983, B&W, Ashland Oil Co., and Slurrytech announced an agreement to commercialize CWS in North America. In late summer 1984, this joint venture, the North American CWF Partnership, reactivated an idle COM plant in South Point, OH, that had operated from 1981 to 1983. The retrofitted plant uses grinders, a KVS ball mill, and B&W pulverizers, and can produce Co-Al at the rate of 20 ton/h (1, 3). Babcock Power in the United Kingdom is planning to start up a plant of similar size in the near future (6, 7). To date, the partnership has slurried over 100 coals from the United States and abroad of widely varying proximate analysis, and has evaluated about 150 additives. The optimum chemical package obviously varies from coal to coal and correlations have been developed to select the most cost-effective option for each specific user (3,10). In Japan, Babcock-Hitachi has gone a step further in the CWSF development process and has developed a simplified process using a two-compartment ball mill with multistage injection of additives. It has been scaled up from a bench scale process to a pilot plant scale process at 5 ton/h (11).

Evaluation and Fundamental Studies

An EPRI-sponsored workshop was held in September 1984 to develop standard laboratory procedures for evaluating CWSFs (12, 13). Under an EPRI contract, B&W performed laboratory tests on six different slurries with similar performance characteristics. Detailed analytical procedures for CWSF characterization were reported for:

- Moisture
- Solids
- Apparent viscosity at ambient temperature
- Apparent viscosity at elevated temperature
- Particle size distribution of constituent coal
- Volatile matter
- Fixed carbon
- Ash
- Ultimate analysis
- Nitrogen concentration
- Calorific value
- Sulfur concentration
- Sulfur forms
- Ash fusibility
- Major and minor elements in the ash by atomic absorption
- pH
- Apparent density
- Stability
- Surface tension by the ring method
- Sintering strength of ash.
- Ash viscosity at high temperatures.

Future methods for sampling, preparation, atomization testing, high shear viscosity measurement, and stability testing were also discussed. Steps have been taken to have the accepted standards included in the American Society for Testing and Materials (ASTM) standards.

Workers at B&W conducted extensive tests on 27 coals to determine the relationship between coal characteristics and slurryability (14, 15). The slurryability of a coal is defined as the solids loading (weight percentage) that can be achieved in preparing a slurry at fixed (specified) particle size distribution, dispersant concentration, and viscosity, at a given shear rate. Coal hydrophobicity is known to increase as the following increase: molar ratio of elemental carbon to oxygen (C/O), fixed carbon (FC), fixed carbon to volatile matter ratio (FC/VM), free swelling index (FSI), and floatability. Slurryability also increases along with these properties. Hydrophobicity tends to decrease with increasing mineral matter content, but slurryability showed the opposite trend. This may be because the total mineral matter increases faster than the specific type of mineral matter detrimental to slurryability. Coal characteristics that correlate well with slurryability are equilibrium moisture, FSI, and floatability. Correlations between slurryability and C/O and water absorption were fair. As expected, hydrophobicity and water absorption are important in determining the slurryability of coals. Workers at Babcock-Hitachi and elsewhere in

Japan have also conducted research on the effects of coal properties and surfactants on the rheological (flow) properties of CWSFs (11, 16).

Atomization and Combustion Testing

Early Testing: Atlantic Research Co., CWSF

In early work (1981-82) sponsored by EPRI, B&W fired 5 tons of CWSF prepared by the Atlantic Research Co. in the former's basic combustion test unit (BCTU) at the Alliance Research Center in Alliance, OH. The eastern high volatile bituminous (HVB) parent coal was also fired in PC form for comparison (17, 18). The slurry was thixotropic (flowed easier after agitation), pseudoplastic, and its viscosity increased with increasing temperature, precluding preheating prior to atomization. The burner used was a scale model of a standard B&W commercial circular oil burner (see Figure 3) and no burner or atomizer development work was done.

In the burner configuration, the combustion air enters through a single adjustable register and is further agitated by the swirler impeller which acts as a bluff body, a static unmoving object. The natural gas ignitor and burner ring (spuds) can be used to fire natural gas alone at full load and was used to preheat the furnace to operating temperature before firing CWSF. The atomizer sprayer plate, a dual-fluid, plain carbon steel nozzle based on B&W's design for firing highly loaded slurries in the pulp and paper industry, is shown in Figure 4. Slurry flows through the central cavity while atomizing air enters through a number of small holes (3- and 6-hole versions were tested) around its circumference. Results pertaining to burner performance are given below:

- Burner design rating: 4 MBtu/h
- Firing range with stable combustion: 3.9 to 4.4 MBtu/h; i.e. turndown ratio: 1.1:1, much worse than for parent PC firing
- Ratio of atomizing medium to fuel mass flow rate (A/F) > 0.05
- Atomizing air pressure: 96 psia
- Combustion air preheat: > 600 °F; no support fuel
- Excess oxygen: 3.4 to 5.5 percent
- Δ Pwf (burner draft loss) = 15 in. water
- Furnace had to be preheated to operating temperature firing natural gas before commencing CWSF firing—Atomizer life: 6 to 8 h (i.e., rapid erosion)
- Slurry pressure at atomizer inlet: 190 to 225 psig
- Carbon conversion: 90 to 93 percent, worse than for firing of parent PC
- NOx emissions: 100 to 200 ppm lower than for PC firing of parent coal
- Flame temperature: 200 to 400 °F lower than for PC.

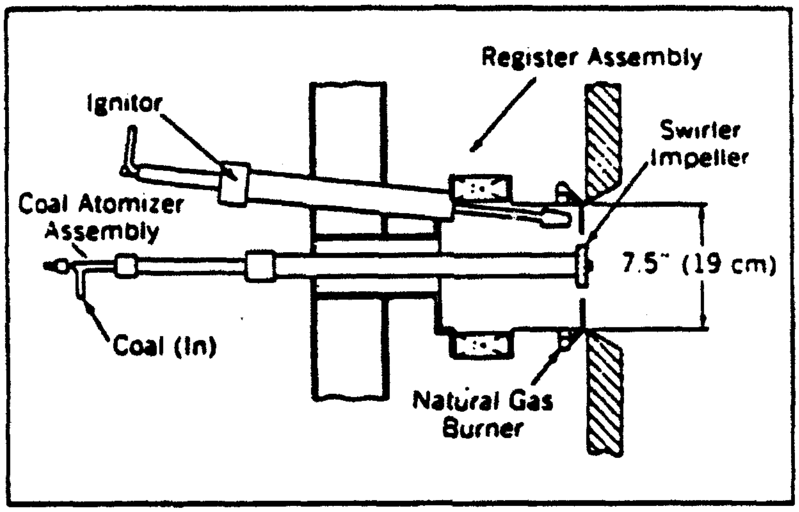
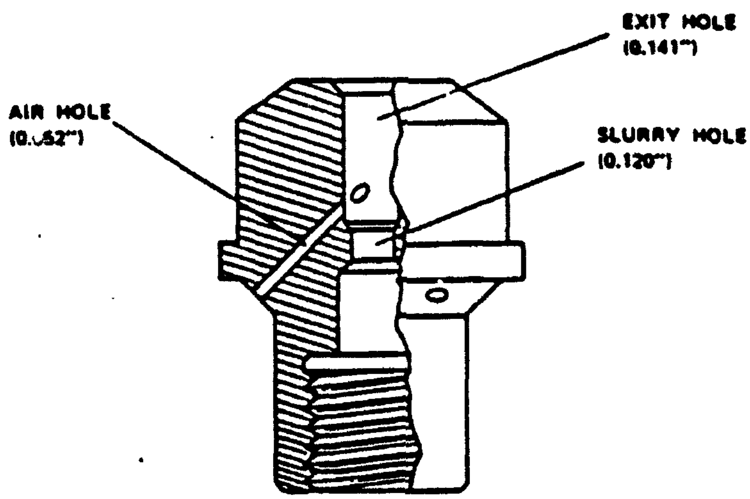


Figure 3. Small scale test burner.



NOTES:

THERE ARE THREE AIR HOLES SPACED 120° APART AROUND THE CIRCUMFERENCE.

THE AIR HOLES ENTER THE EXIT HOLE TANGENTIALLY IN ORDER TO IMPART SOME SWIRL TO THE FLOWING SLURRY

Figure 4. Atomizer sprayer plate.

The CWSF burned much like a very moist coal with a flame temperature that was appreciably lower, hence inhibiting the formation of thermal NOx. However, the conditions of high swirl and the associated increase in combustion intensity had an opposite effect on NOx production. In this instance, the former effect dominated, and NOx production was lower than for the parent PC. At loads below 3.9 MBtu/h, the heat recirculated to the spray was inadequate to sustain a stable flame. Above 4.4 MBtu/h, the high air velocity caused a serious reduction in the residence time of unburnt char, again reducing heat recirculation to the unignited fuel and undermining stability. The slurry was evaluated as having a greater slagging/fouling tendency than the parent coal due to the presence of sodium-based additives. Since the burner was set for maximum swirl, the Δ Pwf was very high. Combustion air preheat was also prohibitively high. Nozzle life was far from adequate.

Combustion Testing of Six Commercial Slurries

In work ending in early 1984, B&W conducted extensive atomization and combustion testing of six commercially available, highly loaded CWSFs (1600 gallons of each slurry) and their parent coals from five vendors: Atlantic Research Corp., Advanced Fuels Technology, Occidental Research Corp., Slurrytech, Inc., and Carbogel. The goal of this EPRI-funded work was to investigate relationships between laboratory properties and CWSF handling and combustion, as well as to develop CWSF specifications for both users and producers (19, 20, 21, 22, 23).

The six slurries studied had solids contents varying from 70 to 75 percent and viscosities in the range of 500 to 2000 centipoise (cP) at a shear rate of 100 s^{-1} at room temperature. (100 s^{-1} means "per 100 seconds." Using the standard ASTM technique, 60 cm^3 of the material is placed in a calibrated metal vessel with a calibrated orifice. The time it takes the material to flow out at room temperature is measured. In this example, it takes 100 seconds for the material to flow out. The unit is also known as Saybolt Seconds Universal [SSU].) The slurries exhibited very little settling over more than 3 weeks of transportation and storage. Static and dynamic stability testing showed similar results, indicating that stability depended on time and not the mode of transportation. Viscosities measured using a rotational viscometer were similar to values obtained from pressure drop data from pipe flow testing, hence flow behavior may be predicted from the former data. Of the six slurries, all were thixotropic, four were dilatant and two were initially pseudoplastic and slightly dilatant at high shear rates. Dilution with water decreased viscosity. Heating reduced the viscosity of three of the CWSFs and this decrease did not change with increasing temperature. For the rest, there was an initial decrease in viscosity followed by a bottoming out at 150 °F, then a steep rise, with the shape of the curve resembling a parabola. Evidently, the viscosity-reducing additives in those slurries either become less effective or break down upon heating above a certain point. Viscosity was found not to correlate at all with the solids loading of a slurry for the six slurries. This suggested that the coal particle size distribution (psd), nature of additives, or coal characteristics determine the viscosity. However, for any one slurry considered alone, dilution to reduce the solids loading did reduce the viscosity.

The fouling potential of a CWSF increases linearly with the percentage of Na_2O in the ash, so additives containing sodium increase the fouling potential of a CWSF over that of the parent coal. Even if a coal is beneficiated to reduce ash content, its fouling potential may be increased if the *relative* quantity of some of the remaining minerals, especially sodium, is increased. Since this 1984 study, the use of sodium-based additives has been discontinued by slurry manufacturers.

Atomization quality is paramount for the stable, rapid, and complete combustion of any liquid fuel, including CWSF. In the ignition zone, smaller droplets ignite sooner, providing heat for the ignition of larger drops. They also have high surface/volume ratios and burn out faster in the furnace. For the six fuels examined, there was no trend correlating atomization quality, given by the droplet mmd, with low shear viscosity. This may be because the shear rates were not representative of those experienced by the CWSF during atomization, which may exceed 3000 s^{-1}. The additives may also induce elastic properties in the slurry; the fluid then should be treated as a viscoelastic and not a purely viscous system. Since a slurry is far from being a homogeneous liquid, viscosity may be related to the ease with which coal particles slip past one another and not due as much to intermolecular forces in the fluid. One important trend for each slurry was that reducing the low shear viscosity by either dilution or heating (only if this resulted in reduced viscosity), as is common practice with heavy fuel oil, improved atomization quality. There was no trend relating atomization quality with surface tension for the six slurries.

Atomization quality was determined in the laboratory using laser Doppler velocimetry. An important disadvantage of the B&W instrument was its inability to measure droplets larger than 160 microns. There were obviously particles in the spray larger than the detection limit, since there were coal particles larger than 160 microns in all six slurries. Therefore, neither the droplet mmd nor the prevalence of the largest droplets, which are most detrimental to combustion efficiency, could be gauged. However, a means of qualitatively comparing atomization performance of the slurries was available. Another limitation was that droplet size distribution (dsd) was measured at only one position—4 ft downstream of the center-line of the spray issuing from one of six atomizer holes. The atomizer employed for all the testing was a dual-fluid, internal-mix, T-jet type (see Figure 5) that characteristically gives a fine spray, though at the cost of a high A/F. In this study, no attempt was made to optimize atomizer design for a minimum, commercial level of atomizing air consumption.

The 4 MBtu/h research burner used for the combustion testing is shown in Figures 6 and 7. It consists of four concentric air zones to allow flexibility in how air enters the furnace. The two outermost zones are equipped with vanes that impart swirl to the airflow. Zone two contains eight natural gas burner spuds that can be used to fire the furnace at full load. The sprayer plate acts as a bluff-body for improved ignition stability. The combustion tests were performed using the burner in the 5 MBtu/h BCTU, a water-cooled horizontal furnace with a nominal residence time of 2 seconds. All six fuels were fired successfully. Results pertaining to burner performance are given below:

- Burner design rating: 4 MBtu/h
- Firing range with stable combustion: 3 to 5 MBtu/h; i.e., turndown ratio of 1.7:1, lower than expected for parent PC firing
- A/F = 0.275 to 0.495
- Combustion air preheat: > 400 °F; no support fuel
- Excess air: 20 percent
- Δ Pwf = 6 in. water
- Atomizer life: 4-6 h (spray plate was of carbon steel construction)
- Carbon conversion: 85 to 94 percent at the rated load of 4 MBtu/h, 20 percent excess air, and 600°F air preheat; lower than would be expected for firing the parent PC
- Slurry was not preheated
- NOx emissions at 3 percent excess air: 430 to 640 ppm.

The importance of good atomization for carbon conversion has been discussed. As in the case of PC combustion, if a large fraction of the droplets produced are above 300 microns in size, carbon conversion is low since these agglomerates take the longest time to burn out. In the present study, the CWSF flames were found to be longer than PC flames due to the CWSF's ignition delay. All the CWSF flames had more sparklers. Sparklers are large glowing particles of char found downstream of the flame, being too large to burn out before leaving the flame. In PC flames, sparklers indicate coal particles above 300 microns are present. Sparklers from CWSF flames had carbon contents in excess of 80 percent.

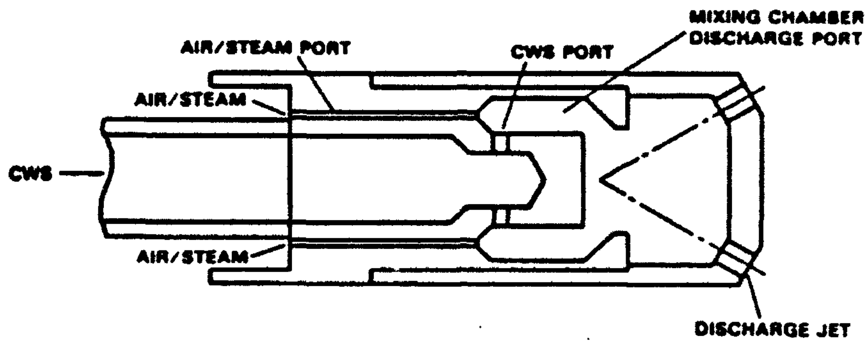


Figure 5. Dual-fluid, internal-mix, T-jet atomizer.

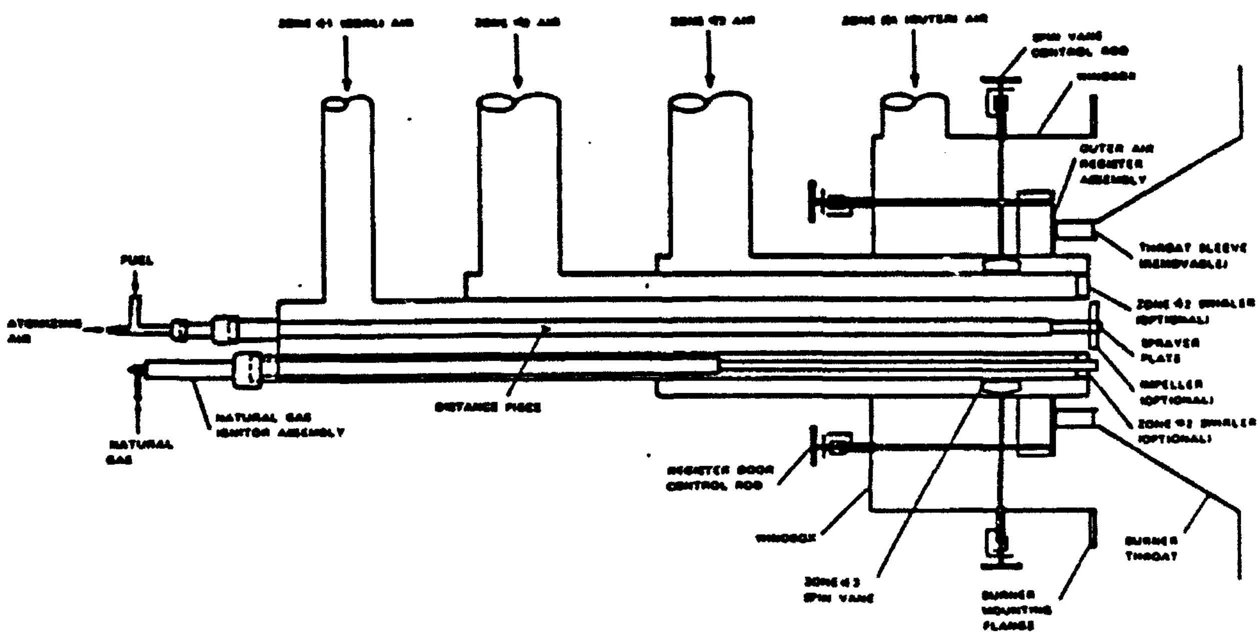


Figure 6. Schematic of research burner.

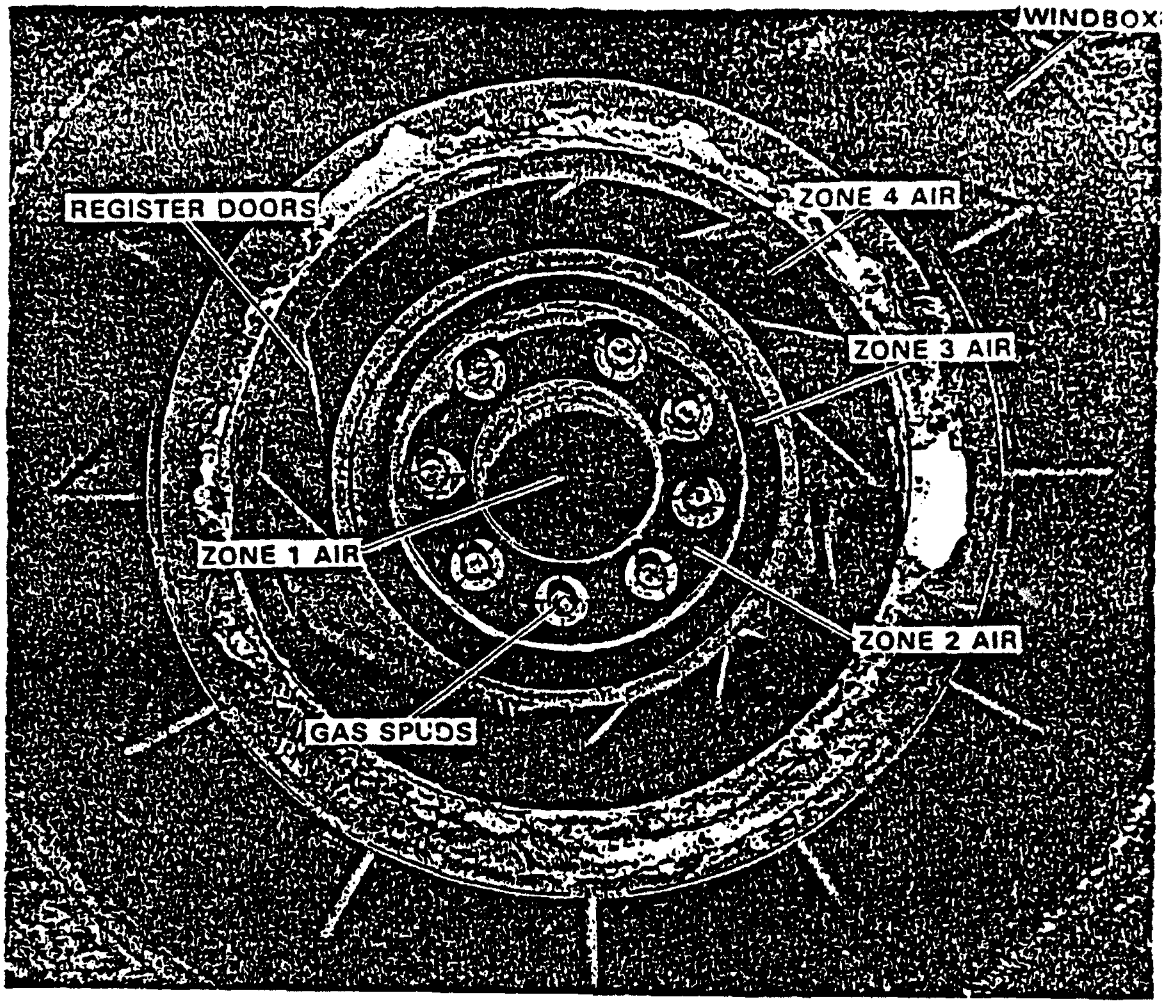


Figure 7. Research burner.

Poor atomization also affects ash behavior, since the fly ash produced is high in unburned carbon. The fly ash particles are likely to deposit by inertial impaction. The unburned carbon can then reduce metal oxides in the slag to metals which have a lower melting point, making the slag stickier and able to trap more fly ash. At the boiler exit, large fly ash particles and those containing much unburned carbon are difficult to retain in electrostatic precipitators. If atomization is good, carbon conversion generally exceeds 99 percent and the fly ash is friable and breaks up into fine (20 microns and smaller) particles.

A/F was found to have an effect on carbon conversion in the present investigation. As fuel increased, A/F decreased and atomization produced larger droplets. Carbon conversion decreased because larger droplets/particles burn slower than small ones. On the other hand, burnout changed little with increasing excess air due to the concurrent but opposing effect of reduced residence time available for combustion.

Based on the work described above, B&W developed the following guidelines for CWSF preparation:

- The highest solids content should be achieved for an acceptable viscosity
- Viscosity should be less than 2000 cP (100 s^{-1}, 78 °F)
- It is preferable that the slurry be thixotropic and its viscosity decrease upon heating
- There is no preference for Newtonian, pseudoplastic, or dilatant behavior

- More than 70 percent of the coal in the slurry should be smaller than 74 microns (fine grinding is useful only if the atomizer is capable of producing a fine spray with a minimal number of coal particles per droplet)

- Less than 1 percent of the coal in the slurry should be larger than 300 microns (large particles not only compromise combustion efficiency, but are more likely to plug the atomizer)

- HVB coals are recommended for CWSFs

- The use of sodium-containing additives is not advised

The main conclusion of this study was that atomization quality is the most important factor affecting the combustion efficiency of CWSFs. A high VM content is the second most important factor that contributes to good ignition stability.

Atomization Testing for Florida Power & Light Co.

In a research program unrelated to the above, B&W was contracted by the Florida Power & Light Co. to determine atomization characteristics of five commercial CWSFs supplied by four manufacturers (24). For comparison, a moderately loaded, additive-free sixth fuel was included. All six fuels were made using the same bituminous coal. A horizontally-mounted T-jet air-assist atomizer with a nominal rating of 6 MBtu/h was used. The fuels were heated in-line to 100 °F before atomization. A Malvern 2200 Drop and Particle Sizer instrument was used to measure spray quality in B&W's large scale atomization test facility. The fuel flow rate ranged from 300 to 600 lb/h, air pressure ranged from 100 to 175 psig, and A/F ranged from 0.125 to 0.6. Spray quality was defined both by the droplet mmd measured and the mass fraction of droplets larger than 169 microns. Results were presented in graphical form and are too voluminous to present here. The moderately loaded reference fuel, being much less viscous, atomized much better than the highly loaded commercial fuels under the same operating conditions (mmd was 15 to 25 microns lower). In practice, however, detrimental effects of the higher water content of the moderately loaded reference fuel may offset any advantages in atomizability. The importance of atomization for efficient combustion has already been stressed. It is also important that an adequately fine spray be achieved at minimal cost. This means that both the air pressure used and the A/F must be minimized to reduce both the capital cost of the compressor needed and its operating cost. This is the incentive for determining which commercial CWSF process yields the most easily atomizable product.

Ultrafine PC or micronized coal (MC) with a fly ash mmd of about 5 microns produces less slag than standard PC, which has a fly ash mmd of about 36 microns, because MC has less tendency to deposit by inertial impaction. Deposition probes inserted into test furnaces clearly show fewer deposits for MC firing. Carbon burnout also is enhanced significantly. B&W researchers conducted atomization and combustion tests on conventional and micronized slurries (CCWSF and MCWSF respectively), both heated and unheated, as well as on PC and MC in 2- and 5-MBtu/h combustors at their Alliance Research Center in Ohio (25, 26, 27). It was expected that if MCWSF produced smaller slurry droplets that burned out faster and yielded smaller fly ash, with a reduced potential for deposition and convection pass erosion, derating could be reduced when firing in an oil-designed boiler. The CCWSF, MCWSF, PC, and MC used in the study were all made from the same coal. The coal used in preparing the MCWSF had a mmd of 9 microns while that in the CCWSF had a mmd of 39 microns. Fly ash from the MC was the smallest. The next smallest ash was from MCWSF that was heated to 175 °F before atomizing using a very high A/F of 3.5, which yielded a very fine spray with only 2 percent of the droplets above 100 microns. Heating beyond 175 °F to 225 °F had little further effect on atomization of the MCWSF. Unheated MCWSF, CCWSF, and PC had larger fly ash of similar size. Carbon utilization basically paralleled the trend described for fly ash. Evidently, grinding the coal to a fine consistency did not improve MCWSF atomization. Heating the MCWSF, which resulted in reduced viscosity, and perhaps also caused secondary atomization (flash evaporation of the water) to occur, produced smaller droplets, smaller fly ash, better burnout, and a reduced tendency to form deposits. Reduced viscosity also means less atomizing fluid consumed (a lower A/F) compared to the CCWSF. Heating the slurry is beneficial only if the additives are not affected and viscosity drops, as was the case with Co-Al and CWSF produced by the Atlantic Research Co.

Ceramic probes were inserted into the flame to estimate deposition characteristics. The preheated MCWSF showed less deposition than the CCWSF. Increasing A/F had a beneficial effect on both fuels due to improved atomization. The strength of the sintered ash produced from firing the fuels yielded an approximate measure of a sootblower's effectiveness in removing ash deposits in convection banks. The MCWSF's sintered ash was somewhat stronger, i.e. more difficult to remove, than that of the CCWSF. This trend parallels the relationship between MC, which is stronger, and PC, but the correlations used were for dry coal firing and may not apply in practice to slurry fuels. In the present study at least, ultrafine grinding of coal used in preparing MCWSF had favorable effects, an observation that is disputed by other workers [27]. Grinding costs should be weighed against retrofitting, derating, operation, and maintenance costs, which would be greater if CCWSF were used instead of MCWSF.

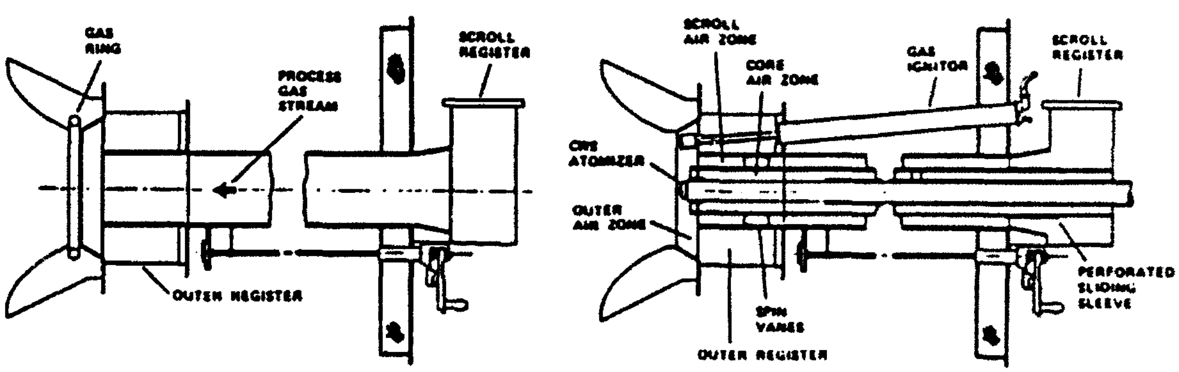
Burner Development

This section discusses chronologically B&W's progress in CWSF burner development. B&W's efforts in this area began with the research burner shown in Figure 6, which was described in the preceding section. In this burner, swirl (the ratio of tangential to axial momentum) could be varied without varying the overall air flow. Initially, Y-jet, T-jet, and racer atomizer designs were tested. A modified T-jet using compressed air and internal premix was determined to be the most promising due to the fineness of spray and superior wear characteristics. Nine different insert materials made of tungsten carbide, silicon nitride, ceramics, etc. were tested for inclusion in atomizer high-wear zones. The atomizer/burner combination exhibited improved characteristics of turndown, A/F, and combustion air preheat over previous efforts at CWSF combustion with oil burners. The burner could also be lighted in a cold furnace.

In a major demonstration burn of CWSF, EPRI contracted with E. I. DuPont de Nemours & Co. to convert and fire an industrial boiler on CWSF. The results of this test are discussed in the next section, **Retrofit Demonstration at Memphis, TN.** DuPont, in turn, subcontracted with B&W to determine burner and boiler modifications and to assist in site preparation and testing. Before the test, EPRI requested that combustion tests of the retrofit burner be done, and these were carried out at B&W's research center in Alliance, OH in a Stirling boiler. The original burner, used for firing waste gas, natural gas, or No. 6 fuel oil [18], and the modified version are shown in Figure 8 (28). Modifications were kept to a minimum upon DuPont's request, and were intended to improve recirculation of hot combustion gases to the flame base. The swirler-impeller at the atomizer tip promotes flame stability via a bluff-body effect, and air passing through the swirler prevents coking of the atomizer's exit holes. A gas ignitor gun extends through the outer air zone. Both six-hole Y-jet and T-jet atomizers (see Figures 9 and 10) were tested. The latter was preferred as it provides a finer spray although a higher A/F is required. The spray angle was optimized at 70 degrees. Too low an angle led to a narrower, darker flame, while too high an angle destabilized the flame by spraying the fuel into the swirling outer air zone. The burner was tested in a Stirling boiler (rated at 50 MBtu/h or 40,000 lb/h of steam at 150 psig) at 15 to 22 MBtu/h, the same range as that of the five burners used in the DuPont boiler. Twenty tons each of medium volatile bituminous (MVB), Co-Al, and "ARC-COAL" from the Atlantic Research Corp. were used. Results pertaining to burner performance are given below.

- Burner rated capacity: 15 MBtu/h
- Firing range with stable combustion: 12 to 23 MBtu/h; i.e., turndown: 2:1 (12 MBtu/h was the lower limit when the combustion air was heated indirectly, i.e., nonvitiated air)

- 600 °F air preheat at 15 MBtu/h, nonvitiated air, 500 °F air preheat at 19 MBtu/h, vitiated air; no support fuel was needed if at least 525 °F preheat of the vitiated air was provided
- High swirl was needed for stable combustion, resulting in a high Δ Pwf of 6.5 in. water at 15 MBtu/h, 600 °F preheat of nonvitiated air, and 10.5 in. water with vitiated air
- Carbon conversion with 600 °F preheat of nonvitiated air was at least 96 percent, compared to 98 percent for PC combustion in the same boiler
- Atomization air pressure: 160 psig; A/F = 0.22 to 0.25
- Cold startup achieved with 600 °F preheat of nonvitiated combustion air; alternative was a few hours of warmup using natural gas or No. 6 fuel oil
- Little atomizer wear after 30 h of operation
- Fuel pressure at atomizer: < 350 psig
- The lowest NO levels of 206 ppm were recorded at 3 percent excess oxygen, 14 MBtu/h, 600 °F preheat
- The highest NO levels of 389 ppm were recorded at 3 percent excess oxygen, 21 MBtu/h, 600 °F preheat.



(a) Original Burner Design

(b) Modified Burner Design

Figure 8. Test burner.

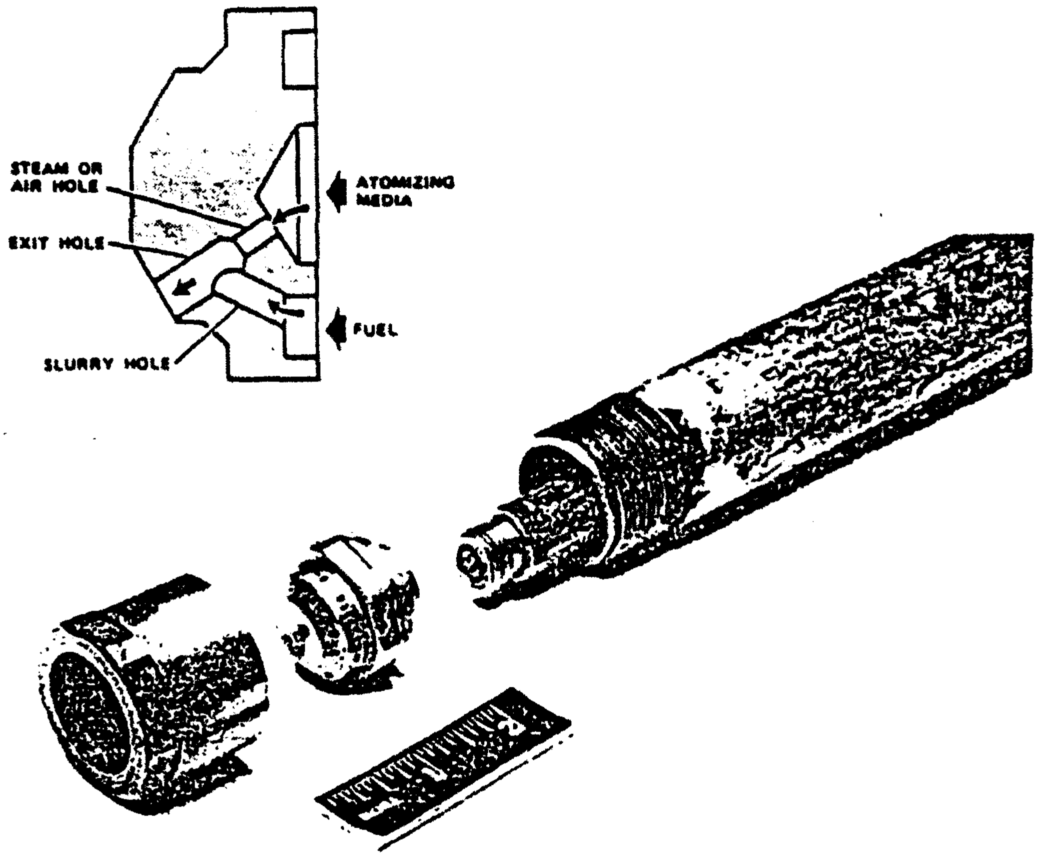


Figure 9. Y-jet atomizer.

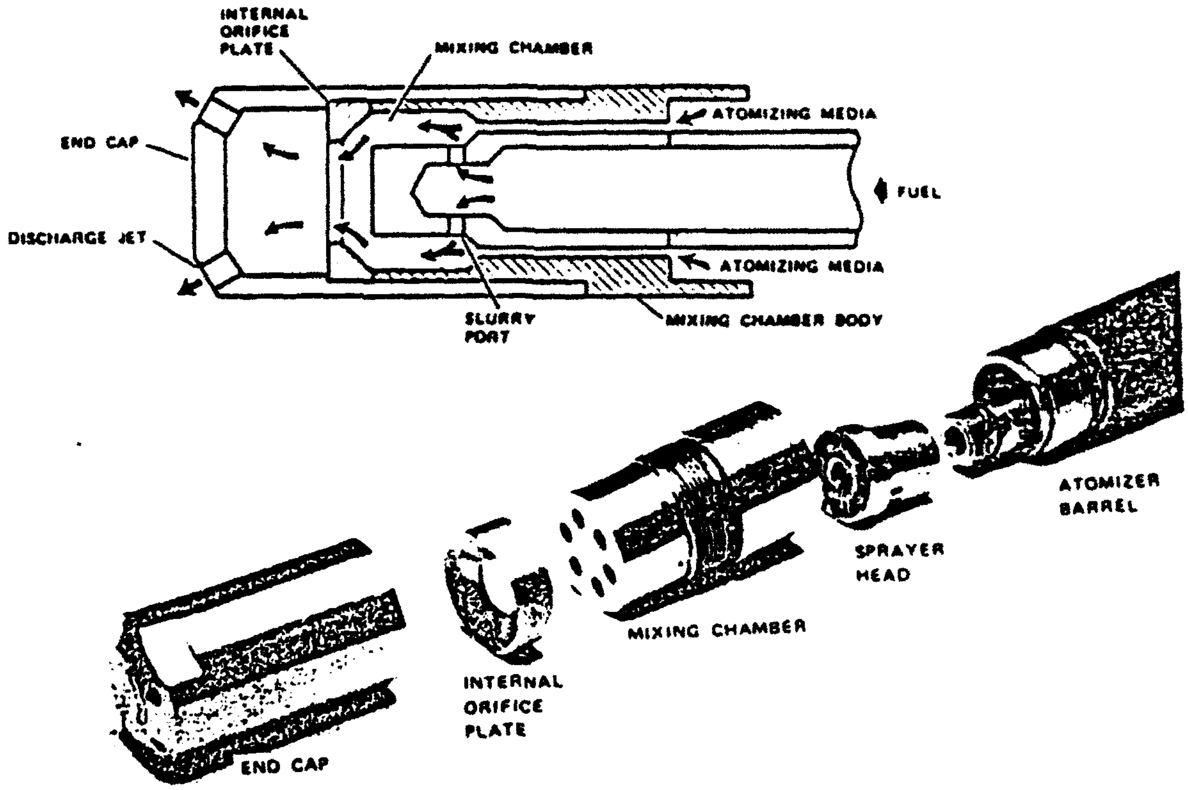


Figure 10. T-jet atomizer.

Direct firing of natural gas into the duct carrying combustion air is an inexpensive way of preheating it, but since the air is vitiated (the oxygen content reduced), flame stability is adversely affected. Indirect heating by means of a heat exchanger incurs an additional cost. A compromise of preheating to only 450 °F with limited vitiation, to 20 percent oxygen, was accepted. A preheat temperature of 338 °F was acceptable but only at a high firing rate of 21 MBtu/h. Excess air levels of 8 to 48 percent were tested with no detrimental effects on flame stability detected. The turndown of 2:1 is poor compared to 3.5:1 attainable with heavy fuel oil using the same burner, or to the research burner already described. Steam at 160 psig was used for atomization and resulted in even poorer turndown and stability since oxygen is depleted at the atomizer tip. With compressed air, beyond an A/F of 0.22 there was no improvement in atomization. Based on the results of B&W's testing, the following modifications to the DuPont boiler were suggested:

- The existing combustion air forced draft (FD) fan could provide only a Δ Pwf = 3.5 in. water and had to be replaced with one that could allow pressure drops of up to 9 in. water

- Only vitiated air preheat capability was available, which would have led to unacceptably high oxygen depletion had it been used alone, so it was to be partly displaced by direct heating using a steam coil preheater. The reduced amount of direct firing was to provide a temperature of up to 600 °F while maintaining the oxygen concentration above 19.8 percent

- Atomizing air compressors capable of providing A/F > 0.25 at 180 psig were to be rented.

Overall, the performance of the modified burner was poorer than that of the research burner that preceded it. This was because the modified burner was constrained by the owner's requirement that in modifying it as much as possible of the original hardware be retained. The following paragraph indicates some of the reasons why the minimally modified burner did not work as well as the research burner.

It is known that a swirl-stabilized flame is necessary for CWSF combustion. But increasing swirl (swirl is the ratio of the tangential to the axial momentum) means increasing the Δ Pwf. In oil-design boilers, the Δ Pwf required is typically below 4 in. water at rated load and the fans are not capable of providing a high pressure drop. Replacing the fan with a more powerful one is an added expense. The alternative is to use proper aerodynamic design of the paths through which air must flow to reach the furnace. That is, the retrofit burner should be compatible with the existing fans.

At B&W, a computer-aided parameter study led to the development of the conceptual burner design (1, 23, 29). This multiple air zone burner with a T-jet atomizer, which was optimized with respect to the size of the drill holes in the mixing chamber and end cap and the spray exit angle, was tested in a B&W model FM membrane wall package boiler. This oil- and gas-designed boiler is rated at 50,000 lb/h and is located at the Alliance Research Center, Alliance, OH. The test results pertaining to burner performance are given below:

- Burner rated load: 40 MBtu/h on CWSF

- Stable combustion over 16 to 48 MBtu/h range; i.e., turndown of 3:1, comparable to that for PC firing

- A/F = 0.13 to 0.16 using air or steam

- Combustion air preheat: > 175 °F, lower than that required in many PC boilers

- Δ Pwf < 5 in. water at rated load

- Δ Pwf < 6 in. water at maximum load

- Atomizer life: T-jet modified to minimize number of wear points and areas prone to erosion protected by wear-resistant inserts. Expected life of > 2000 h

- Carbon conversion: 97.1 percent, comparable to that for PC combustion in same boiler

- Atomizing air pressure: 150 to 180 psig

- Atomizing steam pressure: 130 to 200 psig

- Burner had dual-fuel CWSF/oil capability so that if CWSF firing results in derating, peak load may be reached on oil alone; turndown on oil can easily be 10:1

- Oil ignition system.

This conceptual burner, as a result of the developmental effort, possessed the desirable characteristics of the research burner (Figure 6), but was mechanically simpler and easier to fabricate. Steam generally provided better atomization than air, as evidenced by smaller sparklers in the flame, a higher carbon conversion, and smaller stack particulates. Evidently, steam heats the CWSF while passing through the atomizer barrel and reduces its viscosity, thus improving atomization. Burner turndown, however, was reduced with steam atomization since less air was available at the base of the flame. With air atomization, more oxygen is available for intimate mixing with the fuel in the ignition zone. This is necessary to initiate and maintain ignition during the first critical milliseconds.

In Chapter 2, the importance of hot combustion gas recirculation for a stable flame was discussed. A drawback of this flame pattern is its width, which makes it impinge on the cold furnace walls of tight oil-design boilers. This would not occur in liberally designed industrial and utility applications and in wider coal-design boilers. Further work is planned in reshaping the flame to eliminate the problem. In the present test, flame impingement caused a decrease in carbon conversion with increasing load. Below 35 MBtu/h, light wall impingement resulted in a carbon conversion of 97 percent, based on the carbon content of the fly ash sampled isokinetically (sampling stream was the same velocity as the sampled stream). Above 40 MBtu/h, impingement became significant and large numbers of quenched droplets (sparklers) were observed at the rear of the furnace. Carbon conversion decreased sharply.

The burner described above was developed at the 40 MBtu/h scale from late 1983 to mid-1984. Further improvements resulted in a Δ Pwf of 4 in. water, which is less than required in some PC furnaces. Atomization quality was enhanced to the extent that about 4 percent of the droplets produced were above 260 microns and carbon burnout was 1.5 percent lower than for PC firing of the parent coal. When the slurry was heated to above 200 °F to lower the viscosity, oversize droplets fell to around 2.5 percent, with burnout being only 0.5 percent lower than for PC. This value was about as small as could be attained since it corresponded roughly to the fraction of coal particles in the slurry above 260 microns. Obviously, atomization cannot reduce the size of the individual particles in a slurry. The atomizer life was estimated to be about 1,000 h.

By late 1984 the improved version of the 40 MBtu/h burner (Figure 11) was scaled up geometrically to the 100 MBtu/h size (3, 10, 25, 30, 31, 32). Not having a large enough test facility, B&W conducted performance tests of this burner at Riley Stoker Corporation's Research Center in Worcester, MA, in October and November 1984. This test was the first of four evaluations of large commercially available utility burner systems included in EPRI's "Big Burner Shoot-Out Project." Burner design details have not been released for proprietary reasons. A patent application has been filed with the U.S. Patent Office. CWSF for the test was ARC-COAL produced by Atlantic Research Corp., the slurry consisting of 70 percent HVB coal with a viscosity of 1000 cP at 100 s^{-1} shear rate. It was shipped in 100-ton rail tank cars from the supplier to the test site. The fuel supply system was of B&W design and no significant

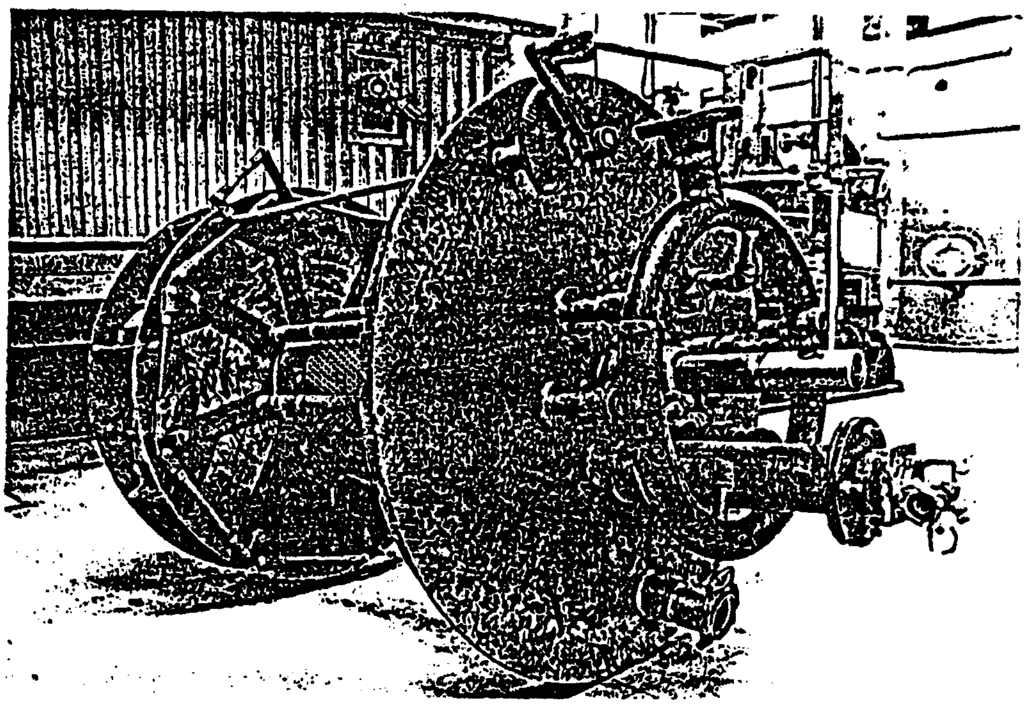


Figure 11. Commercial CWSF burner.*

handling or fuel stability problems were encountered. Burner performance characteristics determined after 100 hours of operation over several weeks were:

- Design rating: 100 MBtu/h
- Turndown of 3:1 with air atomization and 2.5:1 with steam atomization
- Steam and air atomization can be used with A/F < 0.15 for steam
- Combustion air preheat: < 300 °F; no support fuel
- Cold boiler lightoff on CWSF
- Excess air: 15 to 20 percent
- Δ Pwf < 6 in. water burner draft loss
- Atomizer life: extrapolated to be about 2000 h; after 100 hours operation there was no apparent wear of the tungsten carbide nozzles
- Maximum droplet size: 300 microns; corresponds to the maximum coal particle size
- 2 percent of droplets > 260 microns

* This figure is the best available quality.

- Carbon burnout: > 99.5 percent, equal to that for PC firing

- 80 ppm CO and 280 ppm NOx at 3 percent excess oxygen

- Three-fuel capability (CWSF-No. 6 oil-natural gas) for full load operation; 12:1 turndown and A/F = 0.09 when firing No. 6 oil.

The merits of slurry preheating were investigated during testing of the 100 MBtu/h burner. For unheated fuel, atomization was good but carbon conversion was approximately 1 percent below that for PC firing. With preheat, it was equivalent to that for PC. Transferring between CWSF and oil occurred smoothly following a brief automated flush. Since all the performance goals were met, EPRI rated the B&W burner excellent. Since the testing of the 100 MBtu/h burner in late 1984, B&W has continued development efforts which have led to modest improvements in sever ˙ of the performance criteria listed above. Some test results have been published (10, 18) and the rep • to EPRI is available (19). A summary of the latter has been published elsewhere (20) and is not reported here.

Retrofit Demonstration at Memphis, TN

In a major demonstration, EPRI tested a second generation CWSF burner design modified by B&W in a converted boiler (2, 7, 25, 33, 34, 35 36). Over a 35-day period during the summer of 1983, 2000 tons of ARC-COAL and 400 tons of Co-Al were burned in a boiler owned and operated by the E.I. DuPont de Nemours Co. at their Memphis, TN, plant. The boiler was built by B&W in 1951. Rated at 60,000 lb/h saturated steam at 175 psig, it is of standardized spreader-stoker (coal) design but has fired only oil, natural gas (through a ring), or a low Btu waste gas (through the center) through its five 15-MBtu/h burners since purchase. The original burner is shown in Figure 12. Since the furnace dimensions and steam generating tube spacing were designed for coal firing, the capacity was not expected to decrease upon conversion to CWSF firing. Conversion of an oil- or gas-designed furnace is accompanied by the inevitable derating as discussed in Chapter 2. The slurry was transported by rail (cheaper than truck or barge in this instance) from the manufacturers to Memphis. Solids content was 70.3 percent for ARC-COAL and 75.3 percent for Co-Al (which was produced at the 50 tons/d pilot plant operated by KVS in Danville, PA). The Co-Al was transported in four 100-ton rail tank cars a distance of 1053 mi. Heating coils or insulation were unnecessary since it was summer. After 23 days of transportation and storage in the tank cars, less than 0.1 percent of the solids had settled and only slight variations in solids content existed between the top and bottom of the cars. Cleaning the empty cars was more difficult than expected and required the use of an air and water spray system (hydroblasting) to remove residues; cars used to transport ARC-COAL likewise had to be sandblasted. Unloading the Co-Al and ARC-COAL from the cars presented no problems. Both fuels were handled using conventional heavy oil handling and storage equipment without difficulty.

Following B&W's recommendations, the five burners were modified by installing CWSF atomizers, a swirler impeller, and two concentric, annular air zones as shown in Figure 13. Swirl generation vanes were installed in the second annulus. The high secondary air swirl needed for flame stability was to be generated using a new, more powerful forced draft fan capable of Δ Pwf = 9 to 12 in. water. The required swirl was then achieved with the burner register vanes almost fully closed. Eighty percent of the air was swirled in this fashion and the remaining air was primary (intermediate/core on Figure 13) and atomization air. Combustion air was heated in two steps: (1) with steam coil to 305 °F and no vitiation and (2) natural gas direct firing with a duct burner from 305 °F to 500 °F to 600 °F as needed, and oxygen vitiation from 20.9 mole percent vs weight percent to 19.9 to 20.2 mole percent. Modifications to the furnace included the removal of a finned tube economizer which, although compatible with oil and gas firing, would have become plugged with ash. A second furnace access door was installed to permit air lancing (stirring settled ash) of the floor and manual ash removal by hoe and shovel. A retractable soot

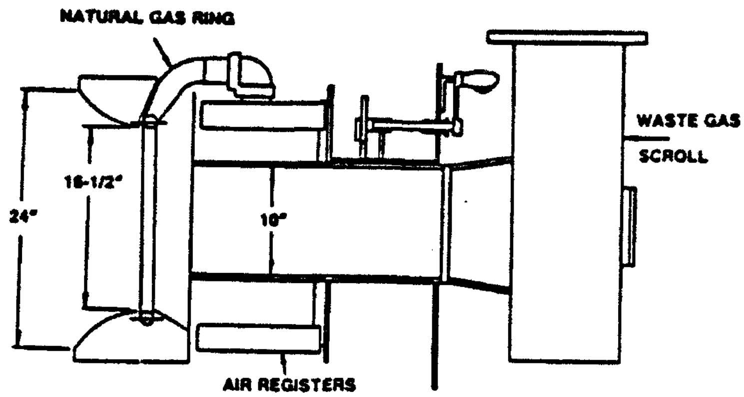


Figure 12. Existing burners.

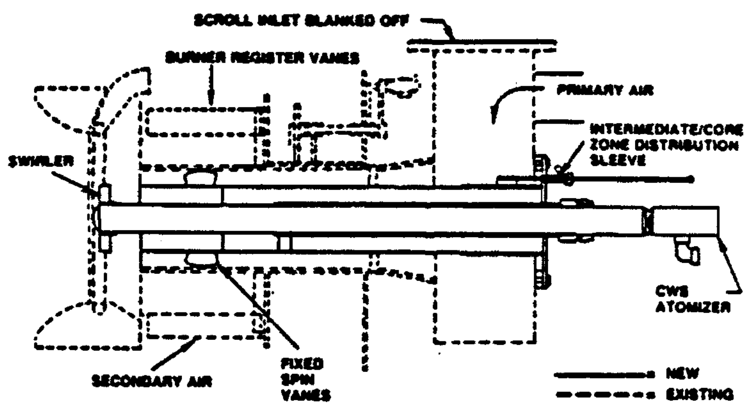


Figure 13. Modified burners.

blower was added at the furnace exit to complement two existing fixed soot blowers. Burner and other performance data is summarized as follows:

- Boiler was capable of being fired at full load of 60,000 lb/h on CWSF (i.e., no derating as expected) using three of five burners with the other two remaining idle

- The three burners were rated at 15 MBtu/h but sustained stable flames over the range 15 to 20 MBtu/h; the turndown was thus 1.3:1 which is lower than the 2:1 ratio noted during testing by B&W

- A/F = 0.25 to 0.3 (over 0.3, no improvement in spray quality)

- Compressed air pressure: 200 to 210 psig; slurry fuel pressure: 170 to 190 psig (air pressure had to exceed slurry pressure by at least 20 psig)

- Combustion air preheat: 375 to 400 °F; no support fuel but natural gas firing was maintained at less than 5 percent of input for flame scanning purposes

- Excess air: 70 to 75 percent; high swirl requirements meant a high Δ Pwf of 9 to 12 in. water; this in conjunction with the fact that the two idle burners were not blocked off led to high excess air levels; it is probable that the three operating burners were at near-stoichiometric conditions

- Atomizer life: 50 to 100 h

- Atomized droplet mmd: 110 microns

- Carbon conversion: 97.9 to 99.4 percent

- NOx emissions: 500 to 700 ppm, not much lower than for PC units due to high excess air levels, which counteract the mitigating effect of a lower flame temperature

- Furnace heat absorption of 50 to 55 percent at 74 percent excess air, rest in convection pass.

T-jet atomizers consist of three major parts (see Figure 14): a mixing chamber that provides initial mixing of the fuel and atomizing medium, an orifice plate that creates an expansion zone, and an end cap with exit holes determining the exit angle (70 degrees in present case) and velocity of the atomized fuel. Standard alloy atomizers typically lasted only about 20 h, after which the spray quality deteriorated. Primary wear zones are shown in Figure 15. Once identified, these zones were protected using tungsten carbide inserts. After 50 to 100 h of operation, the inserts showed no wear but adjacent parts were eroded as shown in Figure 16. End cap erosion limited nozzle life to 50 h and after 100 h the atomization quality

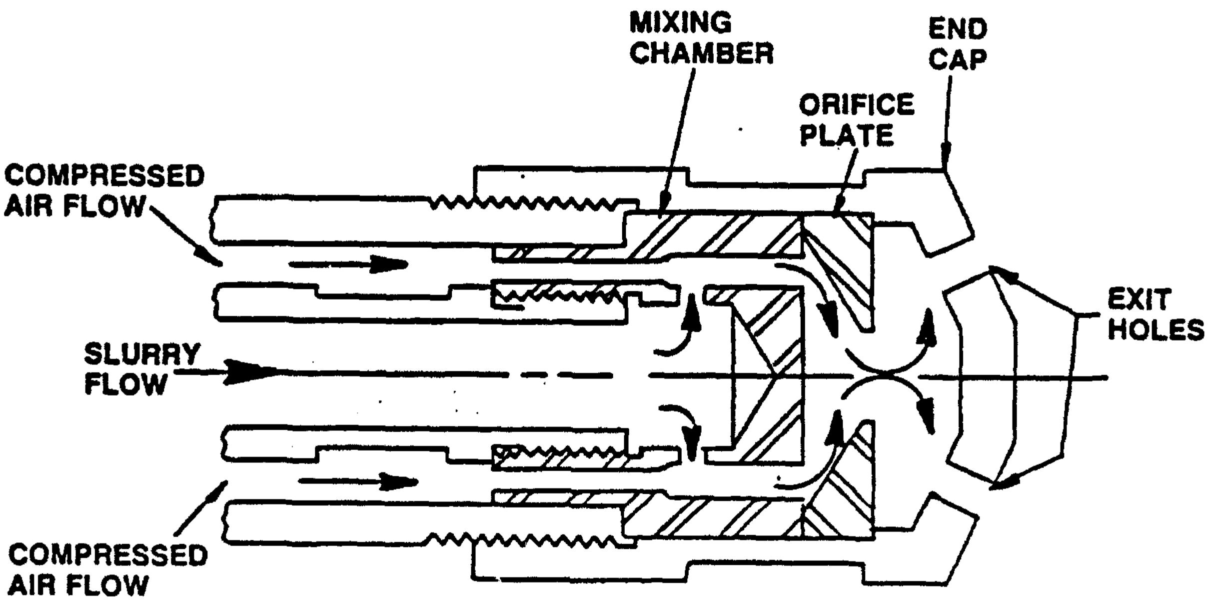


Figure 14. T-jet atomizer with three major parts.

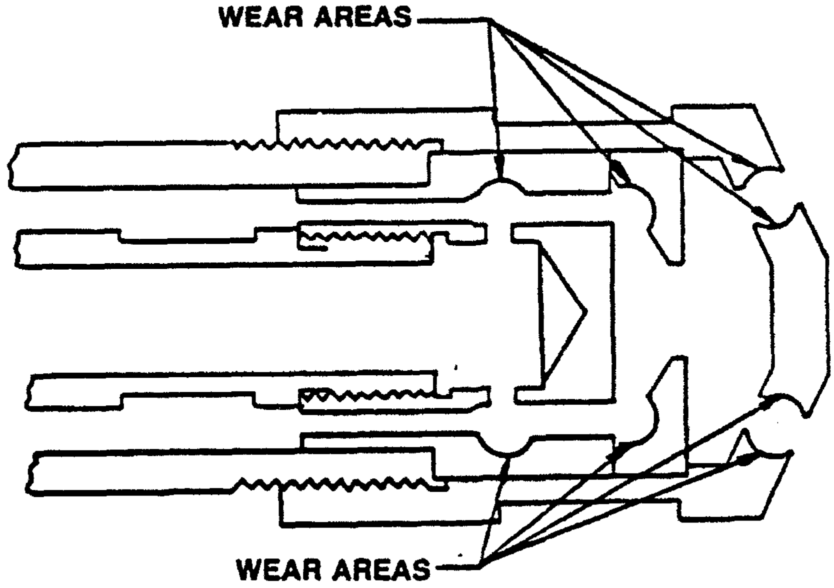


Figure 15. T-jet primary wear zones.

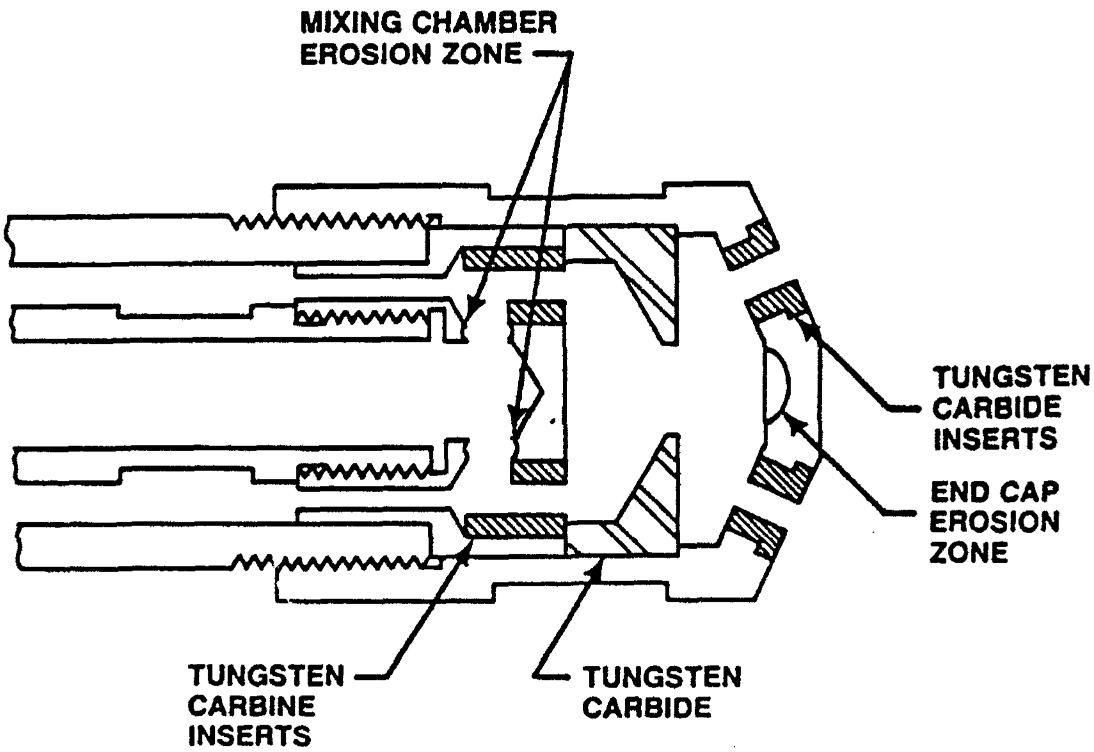


Figure 16. T-jet atomizer secondary erosion zones.

deteriorated due to mixing chamber erosion. If these secondary zones were also wear-protected, atomizer life would increase to over 1000 h. A minimum tip life of 2000 h is considered commercially acceptable while 5000 to 8000 h is highly desirable. The Moyno progressing-cavity, positive-displacement pump showed no wear after 1500 h of operation. Boiler efficiency calculations indicated 73.9 percent on ARC-COAL and 75.9 percent on Co-Al at 70 percent excess air. The difference was due to a higher unburned carbon loss (carbon content of fly ash was 40 percent for ARC-COAL vs 20 percent for Co-Al), higher moisture content, and higher furnace exit gas temperature (FEGT) with ARC-COAL. Firing natural gas, boiler efficiency (78.7 percent) was not much higher than with CWSF, and the difference would be even less if newer burners with 25 to 30 percent excess air and efficiencies from 77 to 79 percent had been used. Standard air heaters (i.e., no vitiation) would also have a beneficial effect. Cold startup on CWSF was unsatisfactory, so startup was on natural gas. Low pressure steam atomization was tried but abandoned since it undermined stability. CWSF flames exhibited full conical development with the base firmly fixed on the sprayer plate. The higher solids content of Co-Al resulted in more sparklers. Dilution from 75 to 74 percent solids decreased viscosity from 860 to 500 cP and reduced the number of sparklers, reduced buildup in bottom ash, and increased the boiler efficiency. B&W and partners produce a highly loaded fuel to minimize transportation costs and suggest onsite dilution to attain the desired viscosity and enhance atomization quality.

The flame from the lowest of the three burners firing CWSF impinged on the flat floor, causing excess ash buildup. Since a furnace bottom hopper was not part of the retrofit, manual ash removal was tedious. Ash deposition was worse than in PC boilers, but ash adhering to tubes was not strongly sintered and was removed by sootblowing. ARC-COAL showed much less buildup on the furnace floor than Co-Al, but the former required more frequent sootblowing (every 2 to 4 h) than the latter (every 4 to 6 h) to maintain a satisfactory FEGT. By comparison, PC firing would have required sootblowing only every 8 h. Over 90 percent of the ash left the boiler as fly ash, which had a mmd twice that of the coal in the CWSFs. It was therefore evident that agglomeration of particles occurs in CWSF droplets. The resulting ash particles are large and possess an increased propensity to form deposits by inertial impaction.

Co-Al combustion resulted in more NOx production than ARC-COAL, presumably because of the former's lower water content and higher flame temperature. NOx levels exceeded those established by USEPA for PC combustion (0.7 lb NOx/MBtu), but standards for CWSF have not yet been established. If considered a coal-derived fuel, CWSF users may be required to meet even more stringent (0.5 lb/MBtu) standards.

Permanent Conversion to CWSF

In October 1984, B&W undertook a project to convert a boiler at their nuclear equipment division manufacturing facility in Barberton, OH, to fire CWSF. Co-Al was to be transported by truck from South Point, OH, to Barberton, 300 mi to the north. The boiler selected is one of two heating boilers and is normally in a standby mode. It is a 65,000 lb/h, B&W-designed, FH-type unit operating at 125 psi saturated steam. It was built in 1948 (3, 10, 30, 37). Being of PC design, the boiler is equipped with a 55 degree sloped hopper bottom and the tube banks are cleaned by six steam sootblowers. There are no sootblowers in the furnace itself. The facility was originally furnished with coal handling equipment, including a pulverizer and bottom and fly ash handling mechanisms. In the early 1970's it was converted to fire No. 2 oil and natural gas and the above coal-related equipment was permanently removed and the hopper bottoms were sealed. After a brief period of operation on No. 2 oil, it has fired natural gas exclusively for a decade. The major additions involved in the retrofit to CWSF were a storage tank, an agitator, a progressing cavity pump, a heat exchanger (to heat slurry to lower viscosity), two 40-MBtu/h burners with dual CWSF/natural gas capability, a main gas burner for startup and CWSF lightoff, and a reinstalled facility for bottom and fly ash collection. The boiler fired over 100,000 gal of Co-Al during the January to April 1985 heating season. It was reactivated in November of the same year. Some burner operating conditions and performance data are given below:

- Burner design rating: 40 MBtu/h, fired at 36.6 MBtu/h
- Atomizing air pressure: 180 psi
- Secondary air preheat: 430 °F; no support fuel
- Excess air: 25.2 percent (this includes furnace air infiltration)
- Δ Pwf: 5.7 in. water
- Slurry pressure: 170 psi
- Slurry preheat: 230 °F
- Carbon conversion: same as for PC in same boiler
- Boiler efficiency: 88.6 percent

Recent improvements in the atomizer now allow either 150 psig air or 110 psig steam to be used. As of March 1986, 600,000 gal of CWSF had been burned over two heating seasons (21) and another 400,000 gal were scheduled to be burned. As of July 1986, 4000 tons of CWSF (about 800,000 gal) of Co-Al CWSF had been used (1, 22). The feedstock was a blend of a HVB "B" coal and a low volatile bituminous (LVB) coal in a 2:1 ratio (23). Details (23) and a summary (20) are given elsewhere. The CWSF combustion system exhibited 96 percent availability over 90 days of operation (over 2000 h) (1, 22). Nozzle wear in unprotected areas revealed that more extensive tungsten carbide protection is necessary.

The South Point CWF Partnership modified a rotary aggregate dryer in Newtown, OH, belonging to the Valley Asphalt Corp. of Cincinnati, OH to fire CWSF/oil. Co-Al was produced at South Point and delivered by tanker truck (3, 37, 38). The retrofit was less complicated and cheaper than for a boiler since no bottom ash disposal or flue gas cleanup was needed. All ash and impurities are simply added to the asphalt mix. The retrofit involved adding three B&W modified T-jet atomizers, a 100-hp air compressor, closing off the air gap at the oil burner, and adding a forced air system to produce the draft and swirl required for coal combustion. When first operated in late 1984, the flame was quenched by the tumbling aggregate and burnout was unacceptably low. Later, a 9-ft-long refractory-lined combustion chamber extension was added between the burner and the dryer drum to provide additional volume and residence time for combustion. Burner operating conditions and performance data are given below:

- Three nozzles fired over the range 9 to 29 MBtu/h, full load was defined by both aggregate throughput and fan capacity
- Atomizing air pressure: 113 to 117 psig
- Secondary air preheat: none since no preheating facility available; No. 2 oil support firing: 1.45 gal/min which amounted to 24 percent of total heat input at low CWSF firing rate and 12 percent at high rate
- Excess air: 5 percent at highest load, > 200 percent at low load due to limited fan turndown

- Slurry pressure at atomizer: 105 to 159 psig depending on load

- Carbon conversion: though not directly measured, the baghouse dust (a mixture mainly of dust from the aggregate and CWSF char/ash) was light brown to light gray in color, indicating acceptable carbon burnout; if a deterioration in combustion quality occurs, the ash/dust mixture darkens noticeably.

In the above retrofit, conversion to CWSF firing meant, in addition to retrofit costs, a greater electricity requirement and more supervision by staff (i.e., manpower) due to the added complexity compared to oil firing equipment. Late in the paving season, after the boiler had been used, slagging began to develop in the combustion chamber. Adding a slag tap partially relieved the problem. Due to the nature of the paving business, there were intermittent periods of nonoperation (not typical of normal boiler operation). This resulted in frequent plugging of the CWSF piping. Another problem encountered was that the higher secondary air flow with CWSF firing (compared to oil firing) carried more heat out of the flue—heat that should have been used to dry the aggregate.

B&W reports having used about 1 million gal of CWSF in a blast furnace demonstration over a 16-day period (21). Preliminary tests were conducted at an LTV Inc.-owned steel plant where unbeneficiated CWSF use had no adverse effects on steel quality (24).

In a DOE-sponsored project, B&W plans to retrofit an oil/gas designed boiler with a CWSF cyclone burner with slag-tapping potential that would operate under low NOx conditions and a reburning technique involving a secondary fuel burning very rich would be used (6, 24).

Conversion Economics

Studies done to determine the feasibility of converting from oil or natural gas firing to PC, COM, or CWSF involve estimating (1) the extent of derating (if any) and (2) the cost of retrofit expressed in dollars per kilowatt of capacity of converted boiler ($/kW) (8, 39, 40). In studies done in 1982, B&W found that for some boilers, the site-specific factors, including design of boiler, location, cost of fuel being fired and to be fired, rendered the option of converting to CWSF-firing cheaper than converting to direct PC-firing. Six coal- and oil-design industrial and utility boilers in the 15 to 400 megawatt (MW) size range were analyzed and in the instances where derating was required, either slagging and fouling (the FEGT constraint) or gas side erosion (convection zone gas velocity constraint) was responsible. Criteria developed empirically and analytically by B&W were used to assess the six units. The extent of derating was as high as 63 percent and costs were up to $138/kW depending on site-specific factors. Generally, the smaller the boiler, the higher the conversion cost, with utility boilers being the cheapest to convert. Since the extent of derating depends to some degree on the extent of modification, in some cases increasing the total retrofit expenditure may be justifiable and in fact, necessary to attain the desired capacity. The cost may even be reduced if the capacity rises faster than the total cost of conversion. In the utility market alone, B&W estimates that a total of 20,000 MWe of coal-design boiler capacity presently firing natural gas or oil could be converted to CWSF firing with minimal modifications and derating. An additional 100,000 MWe of oil-design boilers could be converted with some derating.

In work similar to that discussed above, B&W performed a study to determine boiler performance, modifications, and the cost of converting an oil-designed utility boiler to a slurry of solvent refined coal (SRC) and water (41). SRC has inherent advantages over coal, such as ease of ignition and combustion, lower ash and sulfur content, that impact favorably on derating.

When converting from oil to CWSF, it is not enough that there exists a favorable price differential between the fuels to make the conversion economically feasible. The total operating costs using CWSF (a portion of which is the CWSF cost) should be lower than when using oil, and the difference should repay the boiler owner the retrofit cost within an acceptable payback period. In 1985 (10, 42, 43), B&W

developed an IBM-PC computer program that determines the cost savings resulting from oil to CWSF conversion. Using the program the minimum price margin required between the two fuels to make CWSF an economical choice can then be determined. The initial calculation performed by the program is that of boiler efficiency, and assumptions are made regarding unburned combustibles loss and radiation losses. However, derating is ignored. Sample calculations indicate that firing PC, No. 2, or No. 6 oils generally yields the highest efficiencies followed by CWSFs and finally natural gas. The boiler efficiency is used to determine the annual fuel requirement. The annual operating expense is comprised of several costs, which may be site-specific, and is related to:

- Coal selection
- Solids loading
- Carbon utilization
- Atomizing steam consumption
- Support fuel firing or combustion air heating
- Fuel unloading, storage, supply system
- Combustion equipment
- Sootblowing steam consumption
- Bottom ash removal and handling
- Particulates removal by baghouse or precipitator
- Ash disposal
- Makeup water.

Particulate removal equipment represents the most expensive item in a retrofit. Other costly items include the fuel storage and supply systems, combustion system modifications, and bottom ash removal equipment. The payback period for an investment may be expressed graphically as a function of the price differential between the two fuels. The attractiveness for a conversion increases with the boiler's size. That is, the fuel price differential required for a given payback period decreases. Some of the factors that affect boiler efficiency and operating costs are listed below.

- The parent coal selection depends on its slurryability, sulfur emission levels allowed, delivered cost to the CWSF production plant, boiler owner's operating cost related to combustion requirements, and the fuel's ash content and behavior.

- A high solids loading in the CWSF means a lower water content, less water to be evaporated, and hence increased boiler efficiency—a 5 percent change in solids loading translates into a 1 percent change in operating costs.

- Poor carbon utilization obviously reduces boiler efficiency; burners must be efficient.

- Atomizing steam consumption (i.e., A/F) was found to have a minor effect on operating costs.

- Purchasing an air heater represents an additional expense, whereas firing natural gas as the support fuel means a higher operating cost. Although the payback period would most likely be longer for the former option, the operating cost following this period would be much lower. However, using an air heater can boost the boiler efficiency and the maximum steam production rate. The decision depends on the owner's preference.

- An electrostatic precipitator has a higher installed cost but lower operating cost than a baghouse; the economic difference between the two options can be slight and may be left to the user's preference or other operational considerations.

5 COMBUSTION ENGINEERING, INC.

OXCE Fuel Co.'s CWSF

In November 1983, Occidental Research Corp. (of Occidental Petroleum Corp.) and C-E Power Systems (of Combustion Engineering, Inc.) formed a joint venture, the OXCE Fuel Co., with headquarters in Windsor, CT. An existing Occidental CWSF pilot plant of 200 gal/h capacity (1 ton/h of feed coal) was relocated from Irvine, CA to CE's Kreisinger Development Laboratory (KDL) in Windsor and began operation in June 1984. An idle Occidental COM demonstration plant in Jacksonville, FL was converted to CWSF production and began producing fuel in July 1984. At 2400-bbl/day (or 800,000 bbl/yr) design capacity, it was a 30:1 scale-up from the pilot plant and uses the same process train, which includes a CE Raymond bowl mill (1, 2, 3, 4, 5, 6, 7). Test batches from the pilot plant have been used in the following: Massachusetts Institute of Technology (MIT) electric utility program, EPRI CWSF evaluation, Adelphi University evaluation program sponsored by the Long Island Lighting Co., and in-house combustion testing at the KVB Engineering Inc. facility in Irvine, CA.

Feed coal for the OXCE process has been a high quality HVB steam coal from Kentucky with less than 6 percent ash, about 34 percent VM, 0.8 percent sulfur, and low slagging and fouling potential. Coal loading is about 70 percent to yield a slurry which is thixotropic and also pseudoplastic in the 1 to 10,000 s^{-1} shear rate range; the viscosity decreases with increasing shear but levels off at high shear. The coal particle size distribution is unimodal. OXCE concentrates on additives rather than exotic particle size distributions to minimize viscosity while maintaining an adequately high loading. Hence, commercially proven grinding equipment with up to 300 ton/h capacity can be used.

The rheology of OXCE CWSF can be represented mathematically by a Casson equation, which is preferable to power law models since the yield stress (the minimum shear stress that must be exceeded before flow occurs) is accounted for, as is the leveling off of viscosity (i.e., Newtonian behavior) at very high shear. Due to its high viscosity at low shear, OXCE CWSF is very stable and does not require agitation during storage for up to 60 days, and it can be transported by any means—truck, rail, or barge. Viscosity decreases substantially in the 10 to 100 s^{-1} range, which coincides with shear generated by pumping. Over 1000 s^{-1} shear rate (extant in atomizer nozzles), the viscosity is lower and constant—essentially Newtonian behavior. By tailoring the slurry rheology, two opposing but desirable properties may be satisfied—high viscosity at low shear for stability and low viscosity at high shear rates for efficient atomization. At constant solids loading, the packing efficiency of the unimodal coal powder is maximized by having a wide dispersion in particle size, which minimizes the viscosity. A mmd of 25 to 35 microns is normally used.

The molecular structure of the dispersant used in OXCE CWSF is also important, since highly loaded aqueous coal slurries when sheared for extended periods of time may thicken to the consistency of a paste. The type and dosage of surfactant are important in wetting and dispersing the new surfaces generated during shear while maintaining the integrity of the surface film on the original particles. During slurry preparation, foam may be generated by displacing air as agglomerates of particles are wetted. Hence, an antifoaming agent is used, improving density and viscosity.

A certain yield stress is needed to prevent sedimentation of particles. This can be generated by an interlocking network of particles and additives. Below the yield stress, the fuel acts as an elastic solid which deforms but does not flow. Above the yield stress, it will flow, as the weak physical structure caused by flocculation breaks up. The thickening agent (stabilizer) generates the yield stress needed to eliminate settling. Chemicals used for thickeners include many water-soluble synthetic polymers, natural gums, modified natural products, clays, and fermentation products. The most effective stabilizers impart strong pseudoplasticity to the slurry; in low dosages they impart a high viscosity at shear rates below 1 s^{-1}, while contributing little to the viscosity at high shear rates critical to atomization. Other additives in

OXCE CWSF are a preservative (biocide) to protect the additives and a pH modifier (to keep pH = 7, neutral) to protect equipment against corrosion.

High shear viscosity provides some indication of a fuel's atomization quality. However, even for the same coal, at constant loading and psd, the atomization quality can vary with the additive package—even when high shear viscosities are similar. Therefore, predicting atomization quality based solely on high shear viscosity is tenuous.

In-house combustion research has been performed by KVB Engineering, Inc. for OXCE to develop CWSF fuel specifications for optimum performance. Three bituminous coals were burned in PC and CWSF (70 percent loading) forms. Viscosity was measured at low shear (0.5 s^{-1}, using a Brookfield viscometer), medium shear (110 s^{-1}, using a Haake Rotovisco viscometer), and high shear (up to 10,000 s^{-1}, using a Burrell rheometer). Cold flow atomization testing was done with a Malvern 2200 particle size analyzer that measured the droplet size distribution by diffractive scattering of a helium-neon laser beam. A 300-mm focal length collector lens provided a particle diameter measurement range of 5.8 to 560 microns. As expected, droplet mmd decreased with increasing A/F, air being the atomizing medium. At A/F = 0.15, the mmd of standard, unimodal, utility grind CWSF was 45 microns and that of micronized CWSF was 35 microns. Bimodal slurries atomized poorly compared to these. A good correlation was obtained between high shear viscosity and atomization quality.

Combustion testing was carried out at 2.5 MBtu/h in a modified firetube boiler rated at 5 MBtu/h. The modified PC and CWSF burners, the latter of standard oil/gas design, are shown in Figure 17. Both have variable vane-angle registers that impart swirl to the combustion air flow. An internal-mix atomizer (tungsten carbide insert in the discharge orifice) developed by KVB for COM was used with the CWSF. The atomizer assembly was water-cooled to maintain fuel temperature below 120 °F. The presence of an extended refractory in the CWSF burner was imperative. Without it, poor flame stability and turndown was experienced, especially with low VM fuels. Results are summarized below:

- 2:1 turndown
- Carbon conversion comparable to that for parent PC firing with at least 3 percent excess oxygen
- Low VM fuels required 1 to 2 percent natural gas assist and still showed lower burnout than parent PC
- NO emissions for CWSF firing were less than or comparable to those for parent PC firing.

The bimodal slurry, which atomized poorly, had a slightly lower combustion efficiency and flame stability than the other grinds made with the same coal. The fly ash size distribution for a high VM coal was similar for the PC and utility grind CWSF, but was slightly smaller for the micronized slurry. In some instances, such as for the low VM slurries, the combustion efficiency dropped with increasing percent excess air, indicating that the combined negative effect of decreased residence time and furnace temperature dominated the opposing, beneficial effect of increased oxygen availability. Raising the firing rate had a similar effect—combustion efficiency was reduced, especially for the low VM coal, due to a shorter residence time provided by the greater air flow.

In anticipation of the utility application of CWSF in the future, OXCE prepared preliminary estimates of the capital and operating costs of a commercial 20,000 bbl/d CWSF preparation plant. CWSF cost was estimated at $3/MBtu free on board (f.o.b.) the plant. Coal costs and transportation from the mine to the plant accounted for 50 to 60 percent of the total manufactured cost. Since the total cost was highly sensitive to the delivered coal cost, the plant location is important. On the other hand, if a "dedicated" CWSF production plant is located close to the utility, transportation costs are reduced, especially since the 30 percent water content does not have to be moved a great distance. A short distance pipeline would be used between the plant and the utility boiler. Additives would be less expensive since long term stability would not be required (slurry production would be closely tied to rate of use) and storage requirements would also be minimized at both sites.

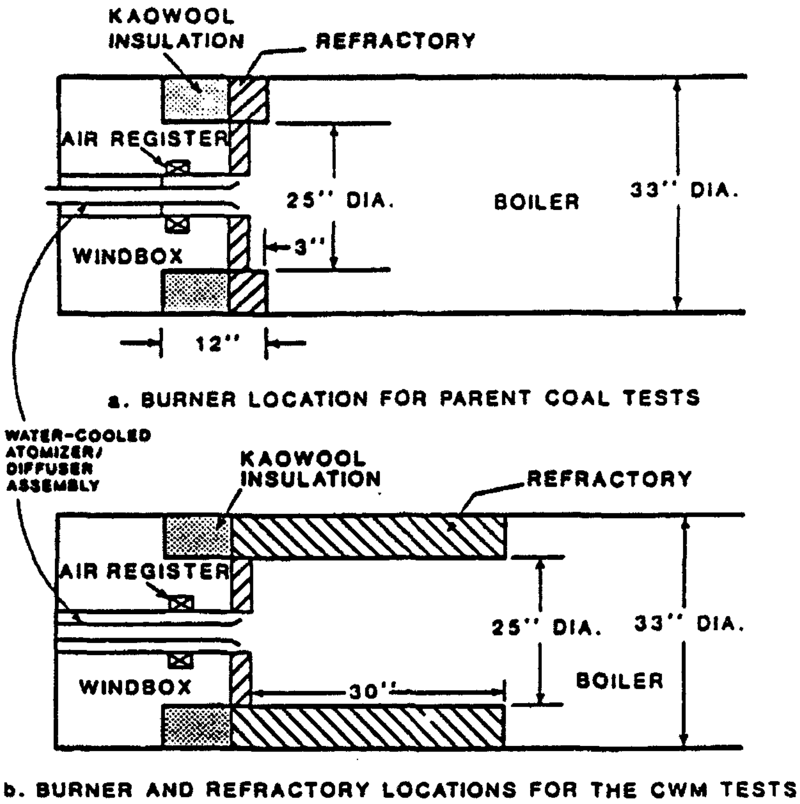


Figure 17. Burner placement schematics.

The economies of scale for CWSF production and retrofitting for CWSF firing indicate that application in the utility sector would result in maximum savings. However, due to the substantial capital expenditure involved in building a slurry plant for utility-scale tests, as well as the long period of time needed for construction and retrofit and the uncertainty regarding future oil prices, OXCE feels that utility commercialization of CWSF will occur some time after CWSF is accepted and used in industrial applications. Since early 1986, the collapse in oil prices has brought marketing, but not research, to a standstill. In October 1985, OXCE signed a contract for fuel delivery with a paper company whose boiler it had modified. In December 1985 the contract was mutually annulled. The demonstration plant in Jacksonville, FL, was shut down. OXCE is concentrating presently on opportunities abroad, such as a pipeline project proposed in the USSR for CWSF transport.

Rheology and Atomization

OXCE workers have identified the significant factors that affect slurry rheology, and hence atomization behavior (8, 9, 10). Initial work dealt with elucidating the effect of coal psd on viscosity for a given coal and additive package. The maximum packing efficiency (mpe) for a given psd is the maximum volume fraction of coal that can be attained. As the mpe is approached, packing becomes increasingly dense and the viscosity theoretically approaches infinity. A bimodal psd is one way of assuring a high mpe. Assuming that the large and small particles differ in size by at least two orders of magnitude, i.e., the interstitial voids between the large particles are like a bulk volume for the smaller ones, the mpe is determined by measurement to be 0.639, which means that 73.5 percent of the filled volume is due to the larger particles and 26.5 percent to the smaller particles.

Empirical equations are available that predict the high shear viscosity of a slurry (8) as a function of the mpe, the actual volume fraction of solids, and the viscosity of the fluid medium, water in the present instance. The predictive accuracy of two such correlations was ascertained by preparing bimodal slurries in the laboratory (mixing a fine with a coarse grind in varying proportions) and measuring their viscosities. By experiment, it was found that there always existed an optimum proportion of the two grinds for minimum viscosity. Plotting viscosity vs the weight percent coarse fraction in the blend, based on theory, yielded two parabolas with the experimental curve, based on test data, nested within the parabola based on the empirical equation, with their minima coinciding. Even though the equation underpredicted viscosity in general, it predicted the optimum fraction of coarse coal for minimum viscosity and the viscosity at this point. A second use of the empirical correlations was in predicting the increase in viscosity with coal loading. For the 60 to 70 percent coal loading range, the agreement was excellent. From this work, it appears that general correlations may eventually be developed for tailoring the coal psd for optimum rheology without extensive slurry preparation and testing.

The primary purpose of OXCE's work on relating slurry rheology to atomization behavior was to optimize the CWSF formulation for efficient atomization while maintaining satisfactory stability and pumpability. A second purpose was to establish optimum operating conditions for atomization. Rheology was measured over a wide range of shear rates; 1 to 10,000 s^{-1}. The stability of a slurry depends on its rheology in the 0 to 10 s^{-1} range, its pumpability on viscosity at moderate shear of about 100 s^{-1}, and atomizability is thought to depend on viscosity at very high shear rates of 2000 to 10,000 s^{-1}. Measurements were taken using a rotational viscometer (Haake RV2) in the 1 to 800 s^{-1} shear rate range and a capillary rheometer (Burrell-Severs Model A120) from 400 to 10,000 s^{-1}. The overlap provided a basis for comparing the two instruments and allowed adjustments to be made to permit the measurements to be equated. Results of the measurements can be described by the apparent slurry viscosity (η_a) which is the ratio of the shear stress (τ) to the shear rate (D) and is given by:

$$\eta_a(\text{cP}) = 0.01\ \tau\ (\text{Pa})/D(s^{-1}) \qquad \text{[Eq 1]}$$

The slurries were prepared from HVB rank coal from West Virginia. Three psds were used: a utility grind was prepared in a bowl mill (32 microns mmd), a micronized grind prepared in a roller mill (19 microns mmd), and a 3:1 bimodal mixture of the utility and fine coal (8 microns mmd) with an overall mmd of 19 microns. Dispersant and stabilizer quantities were the same in all three slurries. It was found that CWSF rheology follows the empirical Ostwalde-de Waele power law model over the entire range of shear rates:

$$\tau = KD^{n} \qquad \text{[Eq 2]}$$

where K is the consistency index and n, the flow behavior index. If n is unity, Newtonian behavior is indicated. Otherwise, non-Newtonian behavior results; dilatancy for n > 1 and pseudoplasticity for n < 1. The apparent viscosity is therefore:

$$\eta_a\ 0.01\ K\ D^{n-1} \qquad \text{[Eq 3]}$$

For the three slurries studied, n varied from 0.6 to unity; that is, from pseudoplastic to Newtonian, but never dilatant. The utility grind fuel showed reduced pseudoplasticity (n increased from 0.70 to 0.82) for $D > 450\ s^{-1}$. Viscosity increased with coal loading from 70 to 71.5 percent. The fit of the power law was good for both cases. The micronized slurry showed pseudoplasticity below $10\ s^{-1}$ ($n = 0.60$) but Newtonian for the rest of the shear range. The bimodal slurry could have been loaded to 72 percent by virtue of more efficient packing but only 70 percent was used for the purpose of comparison. This slurry was Newtonian over the entire range of shear. Its viscosity was always lower than that of the micronized slurry but higher than that of the utility grind for $D > 400\ s^{-1}$, the region critical to atomization.

Atomization testing was done at KVB Inc. in Irvine, CA. The atomizer was a proprietary, twin-fluid, single-port nozzle sized at 2.5 MBtu/h. A Malvern 2200 particle size analyzer was employed. A 300 mm Fourier transform lens allowed measurement of droplets in a range of 5.8 to 500 microns. The droplet size distribution was best represented by the "model independent" distribution. Theoretically, for liquid fuels, atomizability decreases with increasing viscosity. On the other hand, for CWSFs, there is no relationship between the two. In the present work performed by OXCE, however, the apparent viscosity at high shear had a dominant effect on atomization quality. The natural logarithm of the droplet mmd increased linearly with ln(1+ F/A) for 4 < F/A < 20, where F/A is the reciprocal of A/F. This held for all the CWSFs, the stabilizer in water suspensions, and for water without additives. Slopes were greatest for the bimodal grind, lower for the utility grind, and least for the micronized slurry. At any particular F/A, the droplet mmd decreased, and hence the atomization quality increased, in the following order: bimodal > utility > micronized. The mmd of the micronized grind was a very weak function of A/F with an A/F < 0.05 being sufficient for burning. The bimodal slurry required an A/F > 0.13 for passable atomization and the utility grind required an intermediate A/F. For a fixed psd and A/F, the droplet mmd was a linear function of high shear viscosity, where the viscosity was varied by varying the coal loading. Hence, atomization quality was found to correlate well with high shear rheology provided that the coal psd is taken into account. Rheology seems to favor the unimodal over the high loading potential of the bimodal. A bimodal slurry has very efficient packing: interparticle distances are minimized and the particles are more tightly bound to each other by stabilizer molecules. It is therefore more difficult (i.e., the energy requirement, A/F, is greater) to atomize a bimodal than a unimodal slurry.

A curious incidental result of this investigation relates to atomizer design—as the atomizer fuel passage was enlarged slightly, the atomization quality was improved for the utility CWSF but degraded for plain water. In conclusion, though atomization effectiveness generally improves with a decrease in high shear viscosity, the relationship is by no means accurate enough for reliable engineering judgments to be made. As yet, there is no substitute for laboratory measurement of the droplet size distribution in an atomizer test facility.

Atomization/Combustion/Ash Behavior

In a 4-year research contract from DOE's Pittsburgh Energy Technology Center (PETC), Combustion Engineering, Inc. (CE) and Gulf Research & Development Co. carried out a multifaceted program to assess the potential for CWSF use in oil-fired furnaces on a commercial basis (6, 10, 11, 12, 13, 14, 15) The first portion of the program involved combustion of slurries that were made to specification using commercially available burners. Four HVB, low sulfur, Eastern United States coals with high ash fusibility temperatures and good washability (ability to easily remove extra sulfur and ash using only water) characteristics were selected for the study. Eleven CWSFs were prepared from these coals by five different manufacturers (AFT-SOHIO, ARC, CoaLiquid, Inc., Ergon, Inc., and OXCE Fuel Corp.) using their proprietary techniques.

In general, the CWSFs were combusted without support fuel and with good flame stability—sparklers were few. Carbon conversion exceeded 99 percent in all tests at 20 percent excess air and an extremely high air preheat of 900 to 1,050 °F (this was apparently needed due to high heat absorption). Furnace residence times were in the range 0.91 to 1.27 s. The FEGT for the CWSFs was higher than for oil but below that for PC. Short periods of instability were noted due to ash/coke buildup on the burner refractory quarl, which caused some droplet impingement and decreased combustion efficiency. This was controlled by periodic cleaning of the burner.

As found by other workers, combustion efficiency dropped off sharply with increasing droplet mmd. Also, the fly ash size was a strong function of spray droplet size and the combustion temperature—not of the size of coal in the slurry. CWSF and PC had fly ash of similar size. With increasing temperature (at increased firing rate) fly ash for both fuels was larger due to more agglomeration of ash. Surprisingly, the ash from the fine grind PC exhibited more agglomeration that that from the standard grind. The slagging behavior of CWSF was slightly better than that of PC at similar conditions, as measured by a lower drop in heat flux over the 70-hour test period. Waterwall deposits were easily cleanable by sootblowing, as confirmed visually and by heat flux recovery. The tenacity of the deposits varied primarily with furnace temperature. At low temperature, only a dry powder was noted; at high temperatures, the deposits were sintered or molten. The psd of coal in the CWSF had little effect on slagging. As with slagging, gas temperature was the most important parameter affecting ash fouling of the convection tubes—deposits varied from a light powder (for the low temperatures noted during CWSF use) to lightly sintered deposition. Sootblowing requirements were minimal as the powder was very weakly bonded and friable for the coals studied. The coal itself, rather than the proprietary slurrying procedure, had a notable impact on slagging/fouling characteristics of a slurry. Furnace temperature, as already stated, was the other dominant factor.

In following work, CE evaluated the ash performance characteristics of CWSFs (the same slurries that were performance tested) during combustion testing at 4 MBtu/h in CE's fireside performance test facility (FPTF). Furnace conditions—flame temperature, residence time, convection pass temperatures, and velocities—were adjusted to be representative of those in oil-design boilers. The effects of the following parameters were investigated: coal type, slurry processing technique, and extent of cleaning, i.e., beneficiation to remove mineral matter. Baseline PC and oil firing were also carried out. The loading of the HVB, low sulfur eastern United States coals in the slurry varied from 66 to 71 percent. Some of the slurries were dilatant while others were pseudoplastic. Low shear viscosity varied greatly for the same coal depending on the manufacturer and the coal psd. Atomization quality could not be predicted from low shear viscosity.

Combustion testing was carried out with the atomizer operating at optimum A/F and stable flames were achieved for all the fuels without support fuel. Conversion exceeded 99.5 percent at around 20 percent excess air. Furnace residence time, which decreases with increased rate of fire, and droplet size appeared to be the most important parameters affecting carbon conversion. Droplet mmd and fly ash mmd were closely related to burnout. At low burnout both were large, the fly ash because of much unburned carbon in the larger char particles resulting from the largest droplets. At the same firing rate, the heat absorption at any distance from the burner was higher for the CWSF than for PC, due to less ash deposition by the former, but lower than for oil, which was clean burning. The slagging characteristics of each CWSF in practice corresponded to those predicted for the feed coals, but were better than those for PC, as evidenced by a higher heat flux and less deposition. Due to the ignition delay associated with the water content of a CWSF, the temperature-time history of mineral matter is significantly different from that experienced by PC. This may be an important factor in explaining the lower slagging of CWSFs since the temperature-time history determined experimentally is important in ash slagging reactions. These experiments measure the ash slagging reactions as a function of the temperature of the flame zone in the firebox and the time since being introduced into the combustion zone.

Heat flux levels with time were similar for all CWSFs made with the same feed coal, implying that variations in the psd of the coal and the additive package did not have a major influence on slagging performance. Coal beneficiation resulted in a lower rate of slagging and the deposits were less fused and more readily cleaned, as determined by the particles recovered upon sootblowing. Still, when firing in an oil-design boiler, the load must be limited in order to operate below the critical temperature, above which slagging becomes severe.

Besides the properties of the feed coal, gas temperature was a major factor affecting the rate of convective pass fouling and the tenacity of the deposits. Beneficiation reduced this rate but did not affect the physical characteristics of the deposits. Vendor processes did not have a major effect on the fouling propensity of the fuels. The increased rate of deposition noted with increased firing rate indicated the combined effect of more ash loading and a higher gas temperature. Convective pass erosion increased exponentially with gas velocity, i.e., with firing rate, and linearly with ash loading. Coal beneficiation reduced the rate of erosion. The reduction can be more than proportional to the reduction in ash loading especially if abrasive, "bad acting" constituents such as large quartz particles are preferentially removed during beneficiation. As noted with slagging/fouling, the erosion characteristics of the fly ash resulting from the various CWSFs prepared by different manufacturers using the same coal were similar to those of the parent PC, at the same velocity and ash loading.

In other work performed under the DOE-PETC contract, CE evaluated stability, atomization, and other properties of CWSFs. It was found that in general, slurry fuel vendors needed time to gain experience with each new user-specified coal before they could slurry it satisfactorily. Insufficient time meant a fuel that was not optimized. For example, all manner of physical impurities were found in the slurries. Hence it is important to have adequate control over the slurrying procedure to remove impurities that could cause agglomeration and filter/atomizer plugging. Slurries were shipped 2700 mi in tanks. Negligible settling was noted for both the dynamic and static (stationary storage) cases. Corrosion and erosion in pipes varied significantly with coal type, ash content, and vendor process, and was important enough to warrant further investigation. Atomization quality decreased with increasing low shear viscosity. This was a general trend for all the slurries over a very wide viscosity range and was not valid for predictive purposes. The trend was not evident over smaller parts of the range. A similar trend for high shear viscosity was noted over a wide range of viscosity. Fine atomization is important for ignition stability. Moreover, the fraction of top-sized droplets affects burnout since spray droplet size dictates char size. Since volatile matter is the first to ignite and burn out during coal combustion, it strongly influences flame stability and turndown limits—particularly for CWSF compared to PC combustion. This is because slurry droplets are larger than PC particles, and there are fewer fine droplets available to act as ignition sources and flame stabilizers. The magnitude of the calorific value of VM is also an important quantity. Char reactivity affects the speed of heterogeneous combustion and hence carbon conversion. In fact, carbon conversion correlated very well with the coal char reactivity as determined by thermogravimetric analyses and BET (Brunauer-Emmett-Teller) surface areas.

Atomizer/Burner Development and Evaluation

CE's major effort in this area was sponsored by EPRI and involved the development and demonstration of a commercial scale CWSF burner (16, 17). The three-step development program consisted of atomizer development in CE's atomizer test facility (ATF), development of an aerodynamically sound burner register using CE's burner modeling facility, and integration of the two and optimization of combustion performance at 80 MBtu/h scale in CE's full scale burner facility (FSBF). The 20,000 gal of test fuel were donated by AFT-SOHIO. The coal feedstock was a bituminous coal selected by EPRI and cleaned at Homer City, PA, at EPRI's Coal Cleaning Test Facility to about 3 percent ash. Over 150 tons of 70 percent coal loading fuel were produced. The rheology ranged from Newtonian to slightly pseudoplastic. The latter property is desirable since viscosity would be expected to drop at the high shear rates encountered in an atomizer, facilitating atomization. The fuel was shipped by tanker truck to CE's KDL in Windsor, CT.

Of the generic atomizer designs reviewed, the Y-jet appeared to have the greatest potential for success with CWSF. Y-jet atomizers use superheated steam or compressed air to initiate fuel stream breakup through high shear turbulent mixing of the atomizing media and fuel streams. The Y-jet principle has been shown to be effective with viscous fuels. The design's simple geometry with no tortuous paths permits fabrication with erosion-resistant materials (see Figures 18 and 19). CE's experience in Y-jet

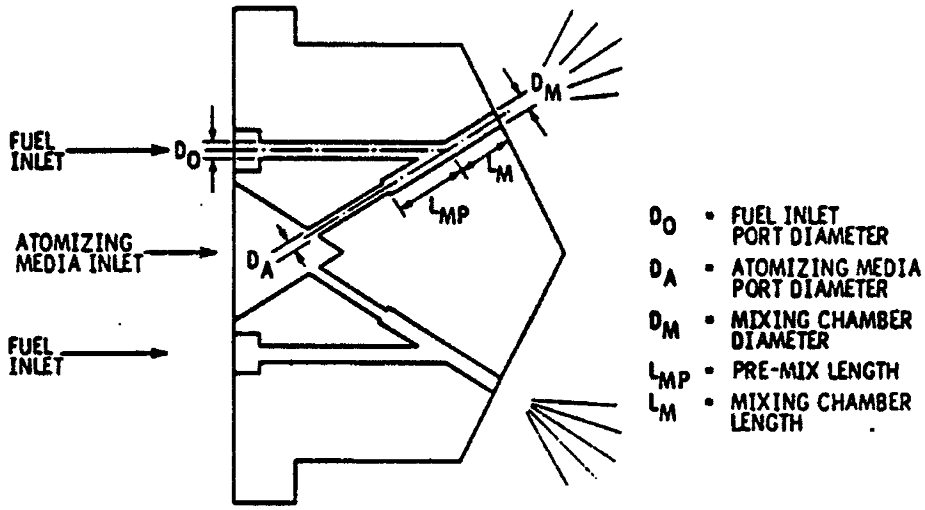


Figure 18. Critical dimensions, Y-jet atomizer design.

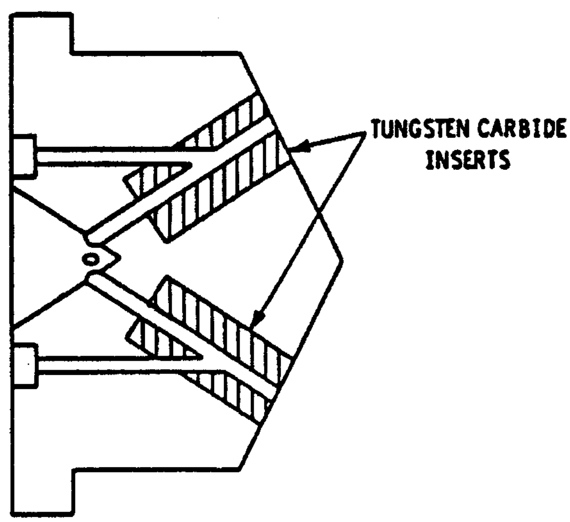


Figure 19. Wear-resistant atomizer design.

nozzles includes a computer design code and full scale ATF. A three-step approach was used in developing the design.

- The critical geometric dimensions (Figure 18) were first quantified based on fuel properties and atomizing media considerations; a CE computer program previously developed for Y-jet performance with heavy fuel oils was used.
- The next step was preliminary ATF testing and performance optimization of the theoretical atomizer design.
- Finally, detailed ATF performance characterization of an optimum atomizer design was carried out over a matrix of operating conditions.

CE's ATF consists of two separate apparatus that can handle nozzles up to 10 gpm size. The droplet size distribution is measured using a laser diffraction technique and droplet ballistics (velocity and trajectory) are measured using a high speed double spark photographic technique. Residual oil atomization in CE's Y-jets yields a droplet mmd around 120 microns, and this was the goal with CWSF. Two different designs were identified by theory, and the superior one was chosen in the second step. This was then subjected to detailed testing. The variation in droplet size with A/F at full load is shown in Figure 20. Increasing A/F above 0.17 did not further improve atomization—the mmd stayed at about 100 microns. From 0.17 to 0.06 there was a gradual decrease in spray quality and below 0.06 it degraded rapidly. Similar trends were noted at lower boiler or burner loads of 50 percent and 25 percent. Hence, spray quality similar to that seen with fuel oil was noted, and the optimum A/F was in the 0.08 to 0.14 range at full load, typical of what is needed for oil atomization. Heating the CWSF prior to atomization from 95 to 150 °F resulted in a slight (< 10 percent) decrease in mmd, probably due to a reduction in fuel viscosity. The improvement was too slight to justify the expense of preheaters in practice. Preheating the atomizing air from 95 to 250 °F had an effect of similar magnitude, and again the added expense was deemed indefensible. At less than full load, the advantage in preheating either the slurry or the air was in any case barely noticeable. Preheating both fuel and air reduced the mmd by about 15 microns. For each case, the benefits gained through a smaller droplet size should be weighed against the capital costs and energy costs that would be incurred. In the present combustion testing program, the compressed air was not heated beyond the normal delivery temperature (with compressor intercoolers removed) of 160 °F. The fuel was delivered to the burner at ambient temperature. The burner register (Figure 21), much like PC registers, establishes a recirculation zone through combustion air swirl and a divergent throat, without which a higher pressure drop would result. Though it is configured for tangential (corner) firing, it is adaptable to wall firing with modifications. As shown in Figure 22, a portion of the combustion air (about 10 percent at full load) is passed through the air swirler and is responsible for establishing the recirculation zone. Together with the refractory-lined divergent throat, the recirculation of hot gases stabilizes the flame both aerodynamically and thermally. Auxiliary air nozzles above and below the refractory are used to duct the balance of the combustion without swirling. This air does not form part of the recirculation pattern as shown in Figure 22. Preliminary testing in the FSBF indicates the following performance:

- 20 to 80 MBtu/h firing range; i.e., a 4:1 turndown
- Flame attached or nearly attached to burner
- Lightoff in a cold furnace with a 5 MBtu/h natural gas side pilot ignitor for the first 15 to 20 minutes (a longer warmup period would be required in field applications where, unlike the FSBF, there would not be extensive refractory lining)
- Combustion air preheat of 250 °F only; 30 percent excess air
- The tungsten carbide-sleeved Y-jet (70-degree spray angle) operated for over 20 hours and atomized more than 100,000 lb of slurry with no measurable wear of the atomizer port diameters that were wear-protected; in comparison, a carbon steel atomizer showed significant wear after only 4 h and 25,000 lb of slurry were atomized.

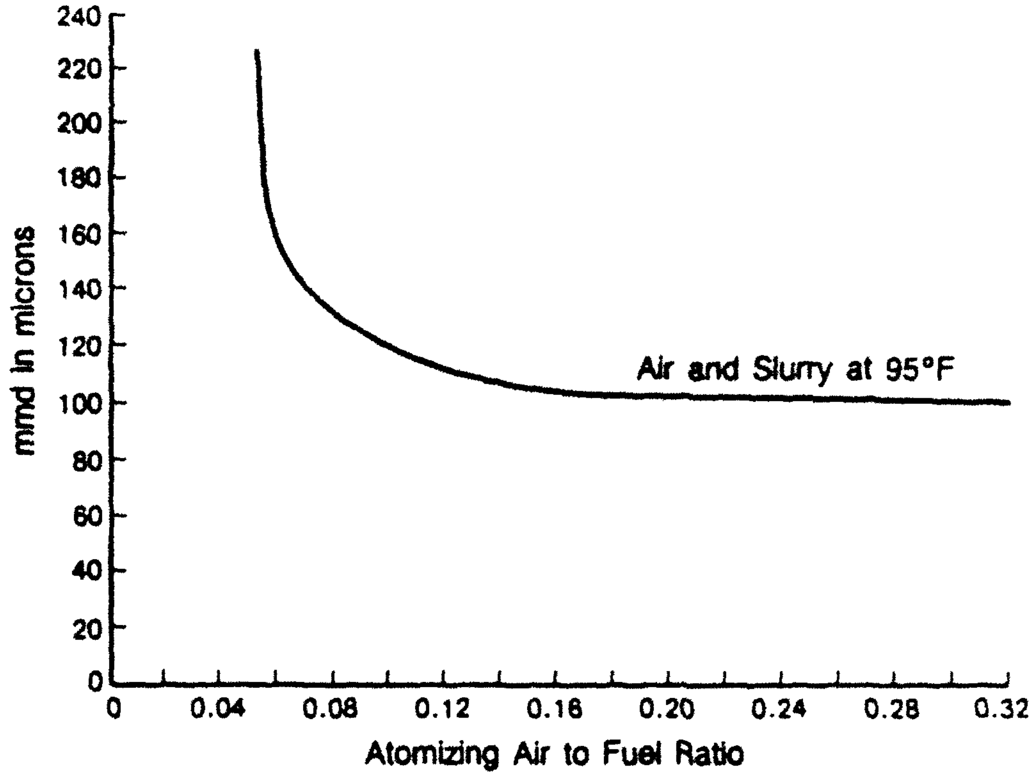


Figure 20. Influence of A/F on atomization quality (100 percent load).

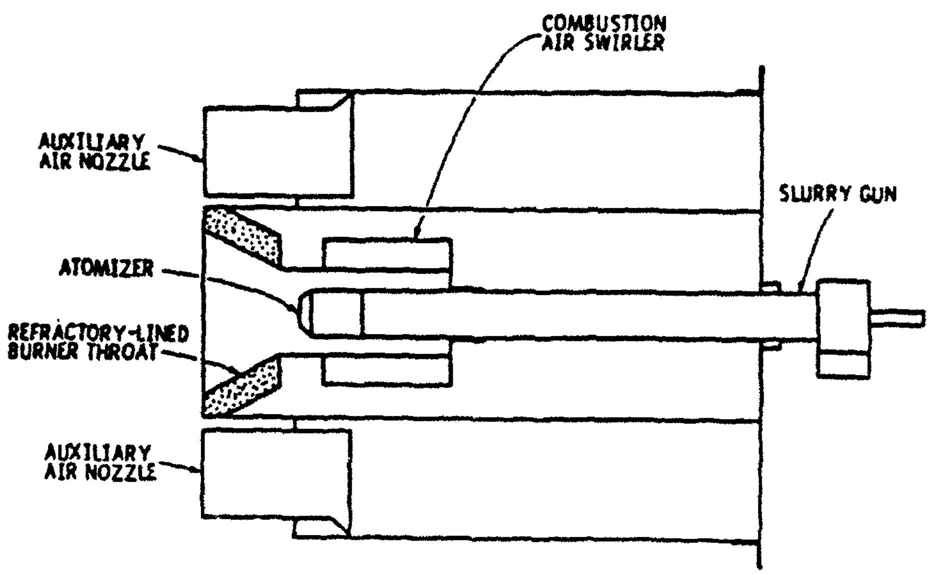


Figure 21. CE coal water slurry burner schematic.

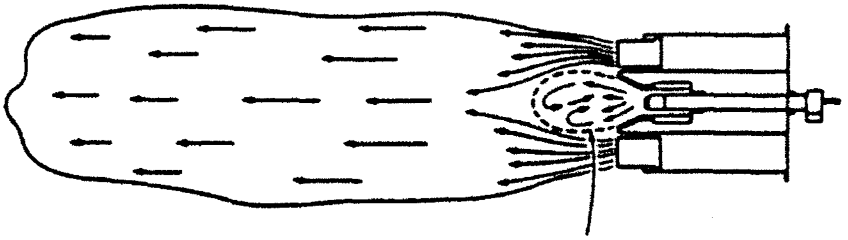


Figure 22. CE/EPRI CWS burner—cold flow model.

The air register described above was also used in dense phase firing of the parent PC in the FSBF using a 70-degree angle diffuser cone. The PC flame exhibited somewhat better flame stability, the bright flame always being attached to the burner. The natural gas pilot flame could be extinguished after only 1 to 5 minutes of warmup. As with CWSF, the length of the PC flame increased with load, but stability and attachment were maintained. Carbon conversion for PC was about 1 percent more than for CWSF over the 40 to 80 MBtu/h load range. The resistivity of the fly ashes from both fuels were similar, indicating comparable collectabilities in an electrostatic precipitator.

Upon completion of the project introduced above, an EPRI report was prepared by CE and the pertinent aspects of this report are given below (18). The coal used in slurry-making was cleaned to 3.6 percent ash in EPRI's Homer City test facility and was further cleaned to 2.6 percent ash (dry basis) during slurry preparation. However, there was a negative change in ash properties since the fusibility temperature was lower, portending an increase in slagging/fouling tendencies—largely due to an increase in iron content. The Thermal Gravimetric Analysis (TGA) char reactivity was similar for the two fuels. Although the coal in the slurry had 30 percent lower BET surface area (probably due to blinding of some pores by additives), the two chars had nearly identical BET areas. It appeared that there were no basic differences in carbon burnout potential between the two fuels when compared on an equal particle size basis (the chars were ground to pass the same sieve).

The Y-jet was designed using a computerized mathematical model. The program estimates atomization performance as a function of fuel viscosity, atomizing media density, A/F, and other parameters. The high shear viscosity of the slurry within the atomizer was apparently much lower than measured at low shear in a viscometer since the fuel side pressure drops were lower than expected and atomization was poor. The orifices were made smaller, which improved spray quality. The fuel had a viscosity of 2600 cP at 113 s^{-1} shear and was pseudoplastic. Dilatancy is undesirable since the viscosity within the atomizer may become high enough to cause plugging and, at least, will reduce spray quality. The shear rate extant within nozzles is estimated to be in the 3000 to 10,000 s^{-1} range. Compressed air was favored over steam as the atomizing medium for two reasons:

- Using steam at high A/F may contribute to derating since the flow rate and velocity would increase and aggravate tube erosion

- Steam in the primary combustion zone may reduce oxygen availability and have a quenching effect on the flame.

It was found that at loads below the maximum, a higher A/F was needed but the droplet mmd was also reduced somewhat. Droplet ballistics were studied using photography. This latter was useful in gauging the prevalence of high momentum droplets which might move rapidly out of the recirculation zone and so affect ignition stability and carbon burnout. Such large droplets should be minimized. High velocity droplets can be accommodated by increasing the combustion air recirculation size or strength. Droplet ballistics were similar to those noted with No. 5 fuel oil (bunker "C"). CWSF droplet trajectories tended to follow the streamlines of a freely expanding jet downstream of the nozzle, just as with heavy fuel oil. Overall, the ballistics data indicated that major deviations from the original swirl-stabilized burner concept would not be required.

The burner design was based on CE's existing commercial design of the direct ignition of pulverized coal (DIPC) burner. The swirl-stabilized DIPC burner features a strong central recirculation zone that recirculates heat and chemically active species to the root of the flame to continuously provide ignition energy to the incoming fuel. A very wide turndown range of more than 10:1 is possible with PC. A full scale model of the burner was tested under isothermal conditions in CE's burner development flow modeling facility. This facility permits aerodynamic modeling of firing systems using helium bubble flow visualization and automatic three-dimensional pitot tube traversing and analysis. It was confirmed that the air register exhibited a strong recirculation zone over the full range of air flow expected. At middle and low loads it was necessary to keep the mass flow of swirled primary air constant while reducing the auxiliary air to maintain a strong recirculation pattern.

Combustion testing was conducted at CE's FSB.², which allows a maximum firing rate of 100 MBtu/h on CWSF or coal and 300 MBtu/h on oil. The burner's combustion performance was parametrically investigated for CWSF and the parent PC. The nozzle had to be prewet with water, which was supplied via a separate line, prior to CWSF atomization, to avoid water loss from the slurry and potential plugging during ignition. Performance characteristics of the burner are given below:

- Stable combustion over 20 to 80 MBtu/h firing range; i.e., 4:1 turndown
- Carbon conversion: 99 percent at full load, 98 percent at half load (about 1 percent below that for PC firing of parent coal)
- 15 to 30 percent excess air; 50 percent at low load
- Air preheat (achieved by direct firing and hence vitiation) of 250 °F was satisfactory; carbon conversion improved with preheat up to 400 °F; no support fuel was used except during ignition and warmup
- Spray droplet mmd of 80 to 120 microns (the coal in the slurry had a mmd of 43 microns)
- A/F = 0.12 at full load
- NOx levels (400 to 500 ppm) with CWSF at full load were similar to those seen with PC; at lower loads, emissions were 50 to 150 ppm lower than for PC.

The PC and CWSF burners incorporate the principle of staging to reduce NOx production from fuel-bound nitrogen. The primary air zone corresponds to the sum of the swirled and atomizing air flows while the remaining (secondary) windbox air completes combustion in the burnout zone. Staging is controlled via individual dampers. As the relative amount of primary air was reduced (at full load and 40 percent excess air), NOx emissions decreased. The "smoke point," the excess air level at which incomplete combustion becomes important and carbon monoxide (CO) emissions exceed 500 ppm, was between 15 and 25 percent. At 25 percent load, the smoke point occurred at 40 percent excess air. However, CO levels were similar for PC and CWSF at the same load. Some darkness was observed at the base of the CWSF flames but not the PC flames. This was attributed to the ignition delay caused by the need to first evaporate the water in the slurry. Carbon conversion was found to increase with firing rate for CWSF, but remained constant for PC. The former effect may be due to an increase in flame temperature due to a lowering of the relative heat loss. Increasing the excess air above 25 percent, for loads between 50 percent and 100 percent, did not improve carbon burnout for either fuel. Through the test period, no "sparklers" or "fireflies" indicating quenched particles leaving the flame were noted at any load for either fuel. The resistivity and collectability by electrostatic precipitation of fly ash from the two fuels was similar. However, the resistivity measurements were taken at high temperature, where the volume resistivity dominates the overall value through the sodium ion conduction mechanism, rather than at lower temperatures at which electrostatic precipitators (ESPs) operate, where a surface resistivity mechanism dominates. Fly ash from CWSFs is expected to contain more carbon, which undermines resistivity, than that from PC firing even at equal burnout. This is because the former fuel is usually beneficiated and so contains less ash per MBtu. Besides collection difficulties, unburned carbon in fly ash poses a fire hazard. Unlike ESPs, baghouses do not depend on resistivity and may be preferable. Additives used in slurry preparation are known to affect fly ash resistivity greatly and so must be carefully studied by the fuel producer. Fly ash size was found to be similar for the two fuels, but ash from the CWSF was very friable and may have undergone size reduction during collection and classification. Hence, depositional behavior by an inertial impaction mechanism could not be predicted. Fly ash sampling was also not representative—there was a tendency for larger particles to drop out of the gas stream at some points.

Atomizer nozzle erosion is undesirable because it degrades spray quality and results in burner downtime. In the work described, soft carbon steel was used as the basic structural material. This reduced the machining costs involved compared to working with hardened materials. Tungsten carbide sleeves were then inserted into the high wear areas (see Figures 19 and 23). As already stated, this 7-hole Y-jet nozzle showed no change in critical dimensions after 20 hours of testing. Of a mass loss of 0.13 percent, most was lost in the fuel inlet points (D_o in Figure 18), which were not wear-protected. Since this dimension was not critical, spray quality was not affected. Determination of nozzle life was beyond the scope of the work.

In September 1982, CE-Canada was awarded a contract to develop an atomizer/ burner arrangement for firing CWSF in a 20-MWe, tangentially-fired, utility boiler in Chatham, New Brunswick, Canada. A four-step procedure was followed in the development work (19, 20):

1. Three promising atomizer designs were selected.

2. These were subjected to cold flow atomization performance testing at CE's KDL in Windsor, CT.

3. The best nozzle was then incorporated into a register, installed in KDL's FSBF, and combustion tested at 70 MBtu/h.

4. The optimized burner was then used in the Canadian project.

The slurry used in testing had a solids loading of 72 percent metallurgical grade coal from Cape Breton, Nova Scotia, Canada. The slurry was prepared in Sweden by AB Carbogel and shipped to Windsor, CT. As explained above, three atomizer designs were chosen and sized at 70 MBtu/h. They were tested in KDL's ATF and compared on the basis of A/F, droplet mmd, percentage of droplets over 320 microns, potential for wear, deterioration of spray quality at low load, while supplying a fixed, reasonable A/F, and amenability to fabrication using wear-resistant inserts.

Based on the criteria, the Y-jet design used in the EPRI contract (Figure 24) was chosen. The top size of the coal in the slurry to be used during actual field testing was initially specified at 175 microns but was then raised by the Canadian steering committee to 400 microns. It is CE's design policy to size the minimum orifice diameter to be ten times the top size of coal in the slurry, to minimize the potential for plugging. Another requirement was that the nozzle be able to function adequately using compressed air at a pressure of only 110 psig (the pressure available at Chatham). The maximum fuel pressure allowable at the nozzle was 150 psig. Hence, a revised Y-jet (see Figure 25) with a minimum fuel passage diameter of 10 by 400 microns was fabricated. The new nozzle produced finer sprays than the previous three at a lower A/F of about 0.1. At optimum conditions (170 psig air, A/F = 0.2), the droplet mmd was 56 microns, which is less than double that of the constituent coal particles (38 microns mmd). Also, only 1 percent of the droplets exceeded 320 microns, another improvement over previous designs. At the conditions expected at Chatham (110 psig air at an economically acceptable A/F of 0.12), the droplet mmd was 80 microns, double that of the constituent coal. Figure 26 effectively summarizes atomizer performance for a smaller nozzle of the same design at all loads (21). It is interesting to note that at reduced load, a higher A/F is needed to attain any given mmd, but the mass flow rate of atomizing media, A, is roughly the same; i.e., A is independent of load. The curves in Figure 26 level off asymptotically at around 40 microns. This is because the coal in the slurry is of this size and atomization cannot be improved further.

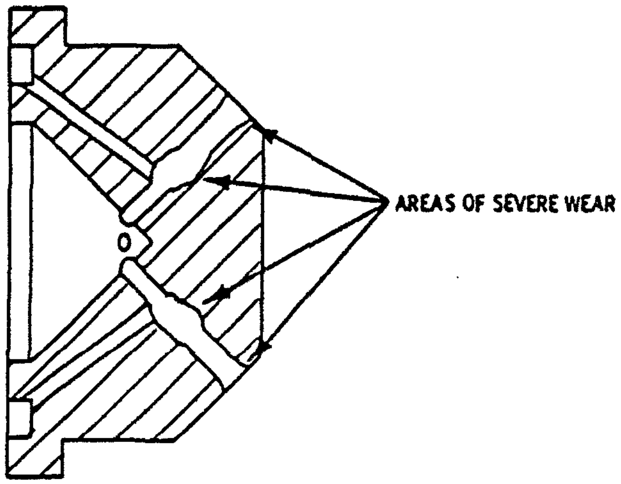


Figure 23. Typical wear problems from firing slurry.

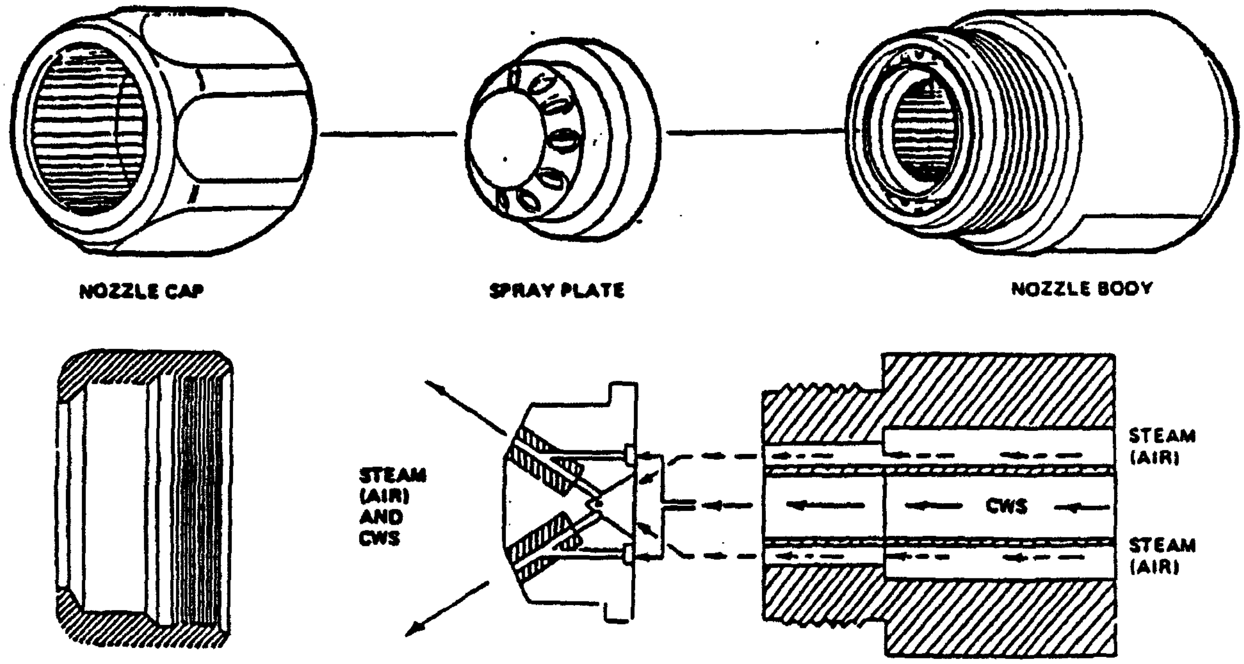


Figure 24. Y-jet atomizer assembly.

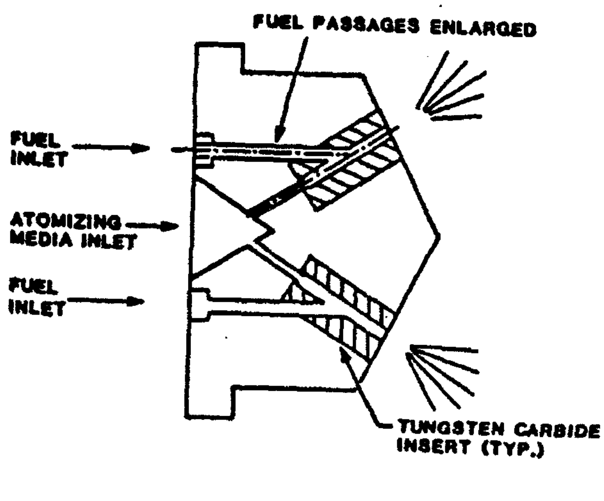


Figure 25. Revised y-jet design.

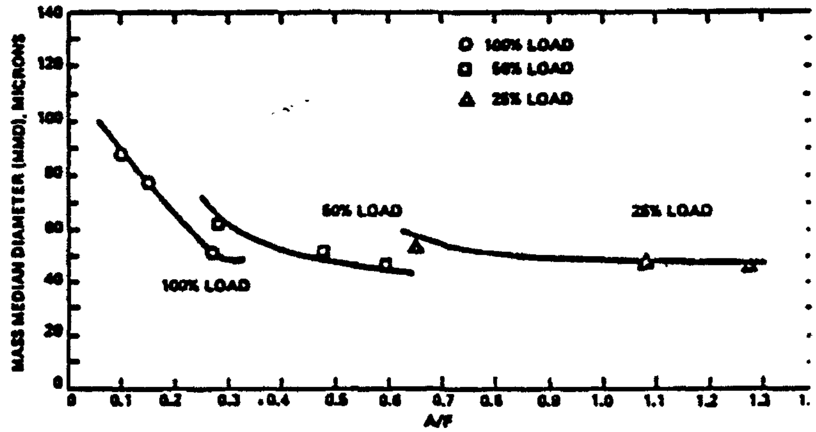


Figure 26. CWM atomizer performance as a function of load and atomizing media/fuel (A/F) mass flow rate ratio (100 percent load = 25 x 10^6 Btu/h heat input).

Combustion testing of the full-scale atomizer/burner combination for the Canadian project was performed at KDL's FSBF. The FSBF was prepared to simulate the Chatham No. 2 unit in terms of heat release rate and FEGT. The windbox was similar to that used in the EPRI-contracted work and is shown in Figure 27. Ten to 15 percent of the total combustion air is sent through the swirler and atomizer and the rest is ducted unswirled through the auxiliary air compartments. To strengthen the recirculation zone, an area in the auxiliary air compartments above and below was bricked off. Since the Δ Pwf available at Chatham was about 2 to 2.5 in. water, the auxiliary air compartments were not fitted with extension buckets in an attempt to minimize the pressure drop (22). Due to the slurry's sensitivity to moisture loss, it was imperative that provisions be made for prewetting the fuel lines and the atomizer gun prior to firing CWSF. Dead legs had to be avoided in the piping and all fuel lines had to be purged with water after unit shutdown. Failure to follow these procedures could lead to drying and adhesion of coal within the pipes, eventually plugging the line.

Burner performance is summarized below.

- Firing range: 23 to 70 MBtu/h; 3:1 turndown
- CWSF ignited in cold furnace with 5 MBtu/h natural gas side pilot ignitor (since refractory-lined test furnace heats up very rapidly, may need to operate natural gas ignitor for a longer period of time during field demonstration in a boiler)
- Combustion air preheat of 550 °F (available at Chatham)
- Spray quality: 68 to 78 microns mmd at A/F = 0.12 to 0.15
- Both air and superheated steam atomization were successful
- Carbon conversion of 94 to 98 percent
- Expected life of atomizer: 500 to 1000 h.

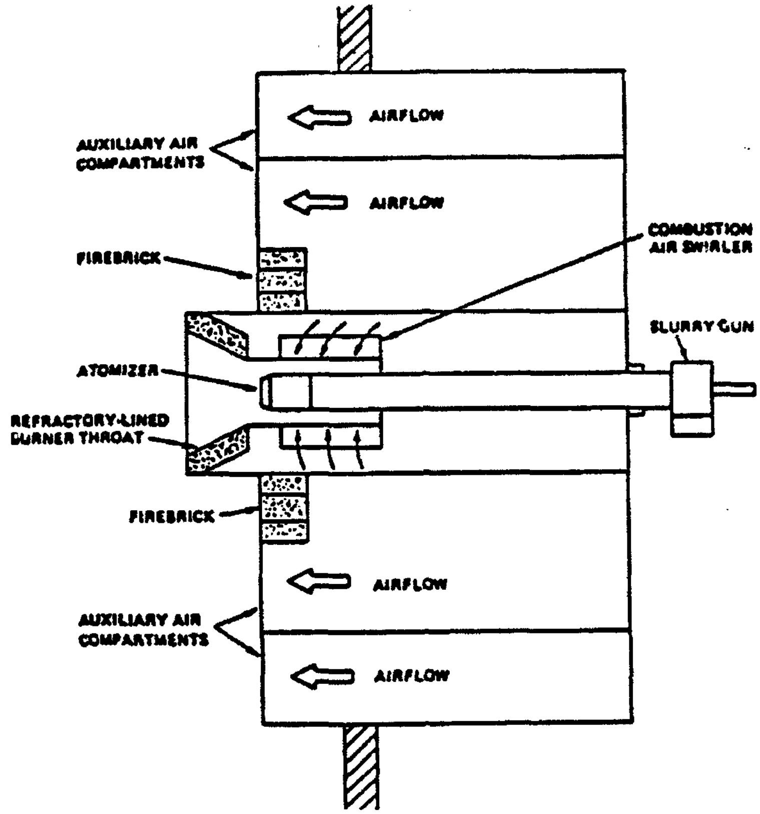


Figure 27. Windbox configuration.

The flame stability and appearance were good. Some sparklers appeared at lower loads. The flame was attached to the burner above 50 percent load and nearly attached below 50 percent. A strong relationship existed between droplet size and carbon conversion:

- Air at 100 psig and A/F < 0.1 resulted in a mmd of 107 microns and burnout of only 94 percent
- Steam at 200 psig and A/F < 0.15 reduced mmd to 51 microns and raised carbon conversion to 98 percent.

As part of CE's joint project with PETC and the Department of Energy (DOE), requests for burners for test purposes were sent to 16 manufacturers, of which 9 responded and 6 were chosen. The six commercially available burners rated at 25 MBtu/h were tested in large scale test facilities. Two of these were CE burners (11, 12, 23). The burners were of the following designs: register-type, refractory chamber, combination refractory and register, rotary cup atomizer burner, high-swirl wall-fired, and tangentially-fired. Each nozzle was installed in the ATF and the droplet size distribution measured. Then, the atomizer-register combination was installed in the subscale burner facility (SSBF) for combustion pretesting and finally, comprehensive testing. Four of the six burners met performance objectives and are described below.

1. High-Swirl Wall-Fired (HSWF). The central primary air register swirls the air through a fixed vane swirler; the remaining (85 percent) secondary air is passed through two concentric, annular, corotational, adjustable-vane swirlers; both air streams are ejected from concentric refractory-lined divergent throats into the furnace; the atomizer is of the air-assist Y-jet type with tungsten carbide inserts specifically designed for CWSF; this burner was designed by CE for a retrofit application in Sweden that is described in the following section, **Retrofit Demonstrations and Permanent Conversions to CWSF.**

2. Refractory Chamber Wall-Fired (REF). Consists of a cylindrical, refractory-lined combustion chamber and air-assist external-mix atomizer; the primary combustion air is partly passed through

a central air swirler and also through properly-angled tunnels that impart additional swirl; the remaining combustion air is added downstream of the burner.

3. Combined Refractory/Register Wall-Fired (REF/REG). Air is passed from a single air plenum through an adjustable-angle vane swirler and the refractory quarl; a slotted metal cone acts as a bluff body to stabilize the flame; atomizer is the air-assist Y-jet variety.

4. Tangential Corner-Fired (TAN). The principal elements are a refractory-lined divergent throat and a fixed-vane tangential swirler, through which the primary air (15 percent of total) is passed; secondary air nozzles supply the balance (85 percent, unswirled) above and below the throat; the atomizer is the same as that used with the HSWF design; this burner was developed by CE for an EPRI project, as already discussed, and a similar burner was used in the Chatham demonstration in Canada; the secondary air is directed toward the firing circle to maintain furnace fireball aerodynamics. In a tangentially-fired, i.e., corner-fired, furnace, the individual flames merge into a single large flame envelope (21).

All burners were fired using the same baseline fuel (69.5 percent HVB coal loading, low sulfur Virginia coal ground to 20 microns mmd). It was found that fuel atomization quality was the controlling factor in combustion. Atomizers that provided the finest spray gave superior performance. The HSWF and TAN nozzles produced the finest spray at any load and A/F (60 microns mmd at A/F = 0.2 with less than 1 percent of the droplets exceeding 320 microns). The REF and REF/REG designs produced droplets twice as large as those from the two burners manufactured by CE. The TAN and HSWF burners operated at reasonable combustion air preheat, A/F, and excess air levels. Turndown was less than desired but ignition requirements were not prohibitive. The Δ Pwf was somewhat higher for the HSWF than for the TAN since all the combustion air is swirled in the former. Carbon conversion was high, especially for the TAN (99.9 percent).

In late 1985, CE tested its TAN burner sized at 100 MBtu/h as part of the EPRI "Big Burner Shootout" project (24, 25, 26). The burner achieved a turndown of 4:1 during combustion testing at CE's KDL in Windsor, CT. Both OXCE and ARC-COAL (the reference fuel supplied by EPRI) were burned. The EPRI performance goals listed below were met.

- Carbon conversion > 99 percent
- Turndown of > 3:1
- Excess air of < 20 percent
- Combustion air preheat of < 300 °F
- Δ Pwf of < 8 in. water
- Maximum droplet size of 300 microns
- A/F < 0.15 with air or steam atomization
- Extrapolated nozzle life of > 2000 h.

Retrofit Demonstrations and Permanent Conversions to CWSF

In the preceding section, CE's development of a burner for the Chatham boiler demonstration in Canada was described. The demonstration is discussed below. In 1982, a multipart project group, which included the Canadian government, sponsored an undertaking to demonstrate the combustion of CWSF in two small utility boilers in eastern Canada (6, 19, 27, 28). A contract was awarded to CE-Canada in 1982 for the development, testing, and delivery of four CWSF burners for the Chatham No. 2 unit located in New Brunswick. The unit is a coal-capable, tangentially-fired, CE balanced draft boiler rated at 22 MWe. Though originally designed as a dual-fuel unit with New Brunswick coal fired in PC form as the main fuel and oil the auxiliary fuel, only the latter was used from 1957 to 1977. Boiler particulars are given below.

- Commissioned in 1956
- Supplies 210,000 lb/h of steam at 900 °F and 875 psig
- Ignition on No. 2 oil
- Configured originally with eight corner-fired coal burners and then with four corner-fired oil guns.

The CWSF burners were installed with the following supply lines: purge water, atomizing and purging air, steam for atomizing oil and CWSF, light oil for ignition, No. 6 oil for oil firing, and CWSF fuel feed. Due to physical constraints, the burners installed in the field were smaller in diameter than the test burner developed by CE. Preliminary field testing of the CE burner began in November 1983, and approximately 500 tons of slurry were fired. Several modifications were needed. Since the maximum Δ Pwf available was only about 2 in. water, a booster fan was installed to generate the swirl needed with the primary air without increasing the pressure of the remainder of the combustion air. Two other changes were extending the auxiliary air compartments (see Figure 28) and addition of refractory to two opposing corners (see Figure 29) to evaluate the effects of increased radiation to the spray root for faster drying of slurry droplets. The modifications were completed in early February 1984, and the new burners were installed by October 1984 (22, 29, 30).

Results reported by the Canadian researchers are discussed below. The unit approached maximum load on both No. 6 oil and CWSF and could be turned down by 50 percent. Boiler efficiency with the former fuel was over 85 percent but with the latter, it fell to about 70 percent, largely because of losses in unburned combustibles and in the dry gas. The boiler was operated from 50 to 100 percent capacity with all four burners on CWSF and no support fuel. Air atomization was mainly used but steam atomization was attempted during one run with good results. Switching guns (from No. 6 oil to CWSF) at full load took about 20 minutes per burner. The atomizers showed negligible wear during operation. The CWSF was not lit off in the cold furnace. The boiler was first warmed up on No. 2 oil followed by No. 6 oil; once the required steam production rate was established, the burners were switched to CWSF.

In November 1984, CE personnel conducted detailed performance tests at Chatham. Operating conditions were:

- Fuel pressure varied from 119 to 162 psig
- Atomizing medium pressure varied from 113 psig for compressed air to 174 psig for steam
- The Δ Pwf for the primary air was 10 in. water

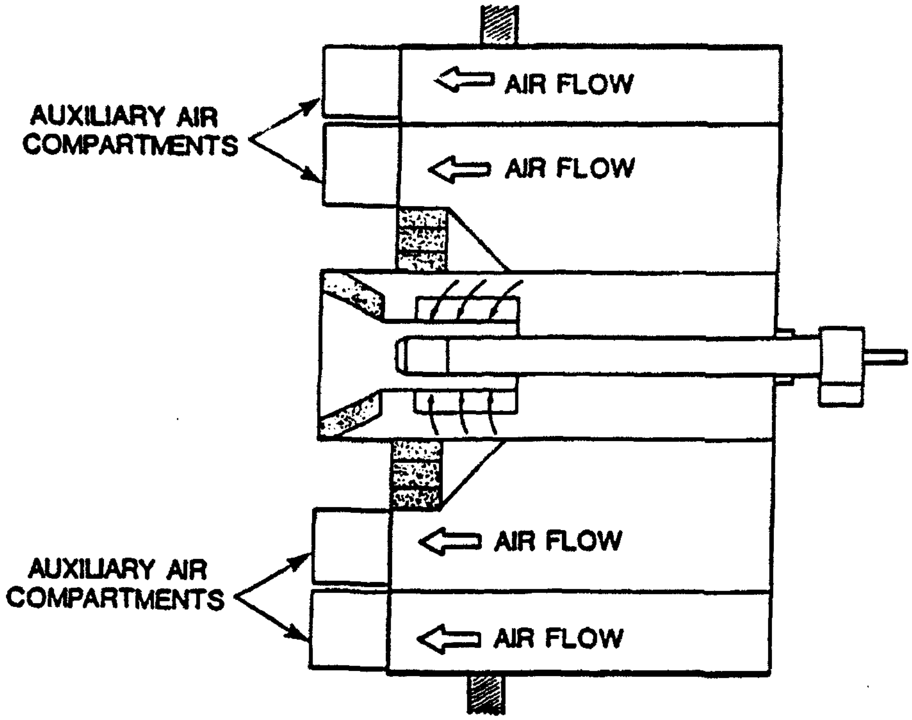


Figure 28. Chatham #2 windbox with auxiliary air compartments.

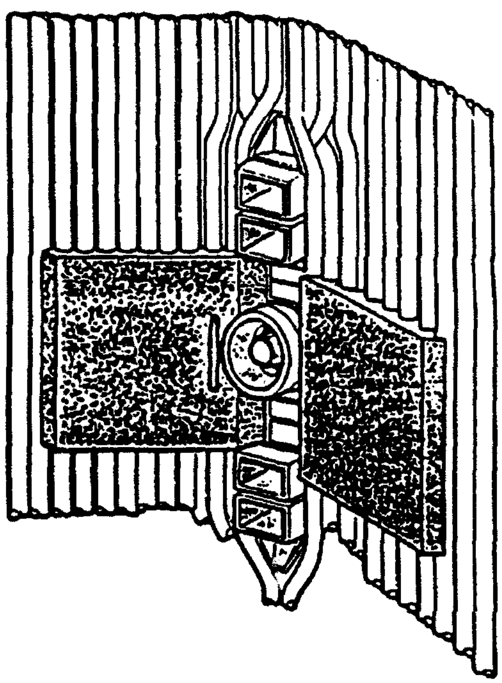


Figure 29. Refractory application on two corners.

- A/F varied from 0.086 with air to 0.124 with steam; these are very low compared to A/F values reported by other workers and are similar to the levels used for oil atomization

- Combustion air preheat was 470 to 480 °F

- Fuel temperature was 82 to 95 °F.

Boiler efficiency on oil was 86 percent; on CWSF it was 74 to 77 percent. Major sources of losses were unburned combustibles and inefficient heat extraction from the products of combustion due to a half-plugged and leaky tubular air heater. There was no significant slagging/fouling noticed during the test program and existing ash handling equipment was sufficient. Other results were:

- Steam atomization provided better flame stability than air atomization

- The turndown of 2:1 fell short of the 4:1 goal

- Carbon conversion averaged a poor 90 percent

- After 400 h of testing, the nozzle showed no wear.

Sweden has made a greater investment in CWSF technology development than most countries due to the scarcity of indigenous fossil fuel reserves. A major demonstration and permanent conversion to CWSF firing took place in Sundbyberg, a city close to Stockholm (6, 31, 32, 33). The boiler is situated in the heating and power plant of the city of Sundbyberg. It was manufactured in 1973 by a CE licensee in Sweden. Rated at 55,000 lb/h steam at 780 psi and 900 °F, it is an oil-designed but coal-capable unit equipped with two oil burners on a side wall. Modifications effected to allow CWSF firing were a new fuel system, a steam-heated air preheater, an air compressor, new burners, a baghouse installed downstream from the existing multicyclone dust removal system, and two additional sootblowers—one for the wall opposite the existing sootblower, and one retractable at the furnace outlet.

A Swedish firm, AF-Energikonsult, had originally developed its own atomizer/burner which it tested thoroughly but found deficient in some respects. Since the project was falling behind schedule, the decision was made to purchase a burner. After evaluating Foster-Wheeler, COEN, and CE products, CE was chosen because of its experience and its extensive laboratory facilities for CWSF burner development at their Kreisinger Development Laboratory (KDL). The burner is a 3-register type that uses a Y-jet nozzle identical to that developed during the EPRI-sponsored program already discussed. CWSF was produced by Nycol AB in a 4 ton/h plant near Stockholm. The fuel production technology was developed jointly with AFT-SOHIO. A HVB Eastern U.S. coal was employed. Slurry fuel with 70 percent coal loading was delivered to the plant by truck, unloaded using pressurized air, passed through a strainer and stored in a tank equipped with a mixer. A feed pump (progressing cavity type) transports the fuel to the boiler front and a recirculation line which bypasses the boiler can be used to return the slurry to the storage tank. Burner supply pumps are also of the progressing cavity type. An indirect air preheater uses boiler feed water with additional preheat provided by steam to give a final air temperature of at least 340 °F. CE delivered the burners to Sundbyberg in February 1983 and field trials began the next month. The new burners exhibited poor atomization quality and aerodynamics and required an auxiliary ignition source to maintain the flame. Hence, a test program was initiated at KDL by CE to revise the design. The modified burners were ready in October of the same year and were started up during the following month. Stable flames were achieved. Performance characteristics were:

- 3:1 turndown, no auxiliary fuel

- 15 to 20 percent excess air

- Atomizing air pressure of 175 psig (high); A/F = 0.16 at full load

- Carbon conversion of up to 96 percent, carbon losses have been as high as 6 to 7 percent (65 to 70 percent of which was found in the fly ash) at all loads

- Only 6 percent of sulfur was caught in fly ash but all the heavy metals, including mercury, were captured in the baghouse

- NOx emissions were low at all loads

- Boiler efficiency on CWSF was 84 to 86 percent and on oil was 90 percent.

After initial problems were rectified, the boiler was capable of providing 98 percent availability—nearly full-time operation. At the maximum attempted load on CWSF, the gas velocity through the convection pass was higher than that allowed by the design velocity for coal-firing. No erosion was observed after the test period. The FEGT limitation did not interfere with operation of the furnace. Load limitations were due to the auxiliary equipment (fans and pumps) and not the boiler or the fuel. It was estimated at the time that the payback period for the retrofit was less than 18 months. However, fuel-related problems developed due to water loss from the CWSF at the fairly high storage temperatures. Remedial measures were to provide a water spray at the top of the tank or employ a slurry with a lower solids loading (higher water content).

Since April 1984 the boiler has been operating continuously on CWSF and is expected to continue in that mode indefinitely. At last report (21, 24) the Sundbyberg unit had accumulated over 2000 h of operation during three heating seasons on CWSF, and the municipality plans to phase in the converted boiler to full commercial operation. The 80 percent of maximum boiler load of 13 MW (thermal) is 150 percent of the boiler's rated capacity on coal, yet there was no slagging/fouling problem. Though gas velocities were higher than the specified maximum, no erosion has been detected. It may be that conventional coal-firing erosion guidelines are somewhat conservative when applied to a CWSF retrofit. Atomizer wear has been minor—not enough to deteriorate spray quality. CE is confident that a commercially acceptable nozzle life (somewhere above 2,000 h) has been attained.

CE has concentrated on sales abroad rather than in the U.S. Besides wall-fired burners used in Sundbyberg, Sweden, as already described, CE will supply sixteen 120 MBtu/h tangential-firing burners for a project in the U.S.S.R. (1). CE considers its burner R&D essentially complete. CE reported the following additional research:

- An optimized 50 MBtu/h wall-fired burner was used with five commercial CWSFs in order to characterize performance differences between the fuels (2).

- The furnace and convection past performance characteristics and retrofit economics of a cross section of CWSFs were determined for several oil-designed commercial furnace types (3, 4, 5).

- In a DOE contract, CE is to develop an advanced coal combustor for retrofit applications that will be able to fire micronized coal in dry and slurry fuel form (6); early work has concentrated on air swirler/burner register design as well as on atomization testing (7).

- The results of the DOE-sponsored research were used to predict the performance of a shop-assembled boiler in Manfredonia, Italy; field data gathered when firing CWSF were compared with the performance predictions (8).

CE demonstrated a 100 MBtu/h version of its tangentially-fired CWSF burner in late 1985 as part of EPRI's project involving large commercial burners for utility retrofit. Partial results are available in the literature (9, 10) and the comprehensive report to EPRI was recently released (11). Salient features of this report are summarized elsewhere (12).

The OXCE Fuel Company continues to be involved in development work and in sales despite the depressed market. Current work focuses on a 3-m diameter pipe loop test facility for studying the formulation and properties required of CWSF for pipeline transportation (13, 14, 15). Pressure drops measured in a 2-m pipe section agreed closely with those predicted using laboratory measurements of CWSF viscosity. OXCE hopes to be involved in supplying and operating a twin-pipeline project between the Kuzbass coal fields in Siberia and an industrial region in the Ural Mountains of the USSR. Other areas of research include the assessment of alkali sorbents in the CWSF matrix for high-sulfur feedstocks, use of lignite and subbituminous feedstocks, and supply of fuel in a CWSF/ natural gas cofiring program at the University of Florida in Gainesville (13). Feedstocks that have been slurried to date include coals from the eastern and western U.S. (including Black Mase coal), China, USSR, Phillipines, and Colombia. Ranks used are anthracite, LVB, MVB, HVB, and subbituminous (15). For highly porous coals, chemical additives that act as blocking agents have been developed to reduce the consumption of dispersants. Thus, moderately high loadings can be achieved even with hydrophilic low rank coals. In 1986, OXCE supplied 100 tons of CWSF produced at their Jacksonville, FL, plant to ENEL, the Italian state-run electricity generation board, for burner testing. The Jacksonville plant is currently in cold standby with a minimum number of caretaking personnel. It can be started up to produce the full rated output within 3 to 5 days of notice (15). In December 1986, 60 tons of CWSF produced at the Windsor, CT, pilot plant were shipped to Cagliari, Sardinia, Italy, for use by ENEL in testing at the 35 MW Santa Gilla Unit No. 2 power station in early 1987. An additional 10,000 barrels of OXCE CWSF was to be supplied in 1987.

Currently, OXCE is formulating micronized CWSF for the CE advanced combustor development program (6, 7) discussed in this chapter. The additives used will be capable of maintaining their integrity when the CWSF is heated to temperatures up to 150 °C (15). OXCE will also supply other advanced combustor program contractors with CWSF through the fuel broker, Energy International, Inc. OXCE won the fuel supply subcontract from Energy International, Inc., over seven other U.S.-based slurry-makers based on cost, technical capability, and commitment to produce the volumes of product required (25). The fuel is to be produced at OXCE's pilot facility in Windsor, CT. A total of 96,000 gal of standard grind CWSF (149 microns top size and 30 microns mmd) and 37,000 gal of micronized CWSF (30 microns top size and mmd of 10 microns) are to be prepared.

OXCE has shown that measuring the extensional (rather than shear) viscosity of CWSF yields an effective analytical tool to test the effect of coal particle size distributions (unimodal, bimodal, micronized) on atomization/combustion characteristics (15, 16, 17). Despite having the lowest shear viscosity in the range of values measured, micronized CWSF had the highest extensional response. Thus, micronized CWSF would be expected to perform worst during atomization and combustion. This was verified during testing by CE. Shear viscosity measurements alone would not have predicted this result.

Derating Studies

The amount by which a combustor or boiler that is not coal-capable would have to be derated for firing CWSF is a complex function of its design parameters, modifications made, operating considerations, and especially fuel and ash related properties. Since 1982 (34) CE has been engaged in theoretical studies for accurately determining the extent of derating suffered by various generic units when using either COM or CWSF made from various coals. As part of their comprehensive research program sponsored by DOE-PETC, CE conducted derating studies on the seven generic oil-designed units described below (11, 14, 15):

- Shop-assembled industrial boiler (100,000 lb/h)
- Field-assembled industrial boiler (400,000 lb/h)
- Box-type utility boiler (400 MW)

- Close-coupled screen utility boiler (600 MW)
- Close-coupled arch utility boiler (850 MW)
- Horizontal box (cabin) process heater (53 MBtu/h)
- Vertical cylindrical process heater (54 MBtu/h)

These load-limiting factors were investigated:

- Convection pass tube erosion
- Convection pass fouling
- Waterwall slagging
- Carbon burnout limitation
- Tube metal overheating
- Inside tube film temperature (process heaters only)
- Working fluid overheating
- Control flow limits.

The derating studies were unique although the test data accumulated for the coals that had been successfully slurried and combusted in earlier phases of the DOE-supported work were employed.

Inadequate residence time for char burnout was the major load-limiting factor with the industrial boilers. For the utility units, convective pass erosion and fouling were the primary load-limiting factors. The process heaters exhibited no derating. The greatest percentage deratings were experienced by box-type utility units and industrial steam generators. The results of derating studies cannot be generalized because of the inter-relationship between factors that include furnace heat release rates, ash properties, and convection pass design. Individual cases should be analyzed by the boiler manufacturer.

In the United States there are about 210 oil-designed utility boilers representing roughly 80,000 MWe of capacity. Another 30,000 MWe of capacity is based on coal-capable units presently firing fuel oil; these units may be preferred initially as candidates for conversion to CWSF. In EPRI-sponsored contract work, CE, Inc. and Bechtel Group, Inc. determined maximum load capabilities (maximum load capability = 100 - percent derating) of four utility boilers upon conversion to CWSF firing. The proposed conversion entailed modifying the fuel handling, firing, and ash removal and handling systems without compromising the capability of returning to oil-firing at full load. Four units made by three major manufacturers (Foster-Wheeler, B&W, CE) and representing the three most common designs in the oil-fired boiler market (close-coupled arch [CCA], close-coupled screen [CCS], and box) were chosen for the study. The units ranged in size from 410 to 850 MW. One low- and one medium-fouling propensity eastern bituminous coal were considered. It was assumed that both coals could be beneficiated to 3 percent ash and then slurries made with a 70 percent solids loading (35, 36). Major modifications deemed necessary to allow CWSF use were:

- Installation of furnace bottom hopper and support; as in PC furnaces, a 55 degree slope with a 4 ft by 4 ft throat was recommended; this would allow ash deposits falling from the furnace to pass through the throat into the ash hopper.

- On the CCS unit, relocation of half of the reheater crossover tubes to increase the transverse spacing and reduce the local gas velocity.

- Depending on the unit, replacement of tube materials for high-temperature problems.

- Replacement of spiral-finned, staggered-tube economizers, if plugging becomes a problem and if space permits.

- Increased slopes of the fly ash hoppers at the economizer, air heater, and gas recirculation duct.

- Addition of two or three levels of furnace wall deslaggers above the firing zone.

- Installation of new burners with air-assist atomizers, as well as air compressors.

In the four units considered, the number of convection pass sootblowers was adequate, but in applications where ash accumulation poses a problem, more may be necessary. All four units operate with balanced draft, and the forced-draft fan capacities were adequate for the derated capacities when firing CWSF. It
is conceivable that in some cases, an inadequately-sized existing forced-draft fan may be the load-limiting factor.

Modifications would be needed to the fuel supply system as shown below:

- New CWSF storage tank, main fuel supply pumps, transfer pumps, burner supply pumps, piping, and associated measurement and control instrumentation.

- Tank must be equipped with low speed agitator to prevent settling of coal particles.

- Tank and piping must be well insulated to prevent freezing of fuel.

The CWSF is delivered to the plant by barge at existing oil dock facilities, but during the winter the latter are closed and the fuel must be delivered by either rail or truck.

The ash removal and handling requirements listed below are a major retrofit expense.

- The existing bottom ash collection hopper must be replaced with a water-impounded hopper.

- Bottom ash is crushed and sluiced to a transfer tank, then sent to dewatering bins, after which it is hauled by truck to an offsite dump; all the pumps and control systems associated with the above process are required.

- ESPs are needed with all units when firing CWSF since uncontrolled emissions would exceed the emissions levels set by applicable State and Federal ambient air quality standards.

- Fly ash must be conveyed from the ESP, economizer, and air preheater hoppers via a pneumatic system to silos, from which it is periodically removed by trucks for offsite disposal.

- The boiler foundation must be excavated to provide space for the new furnace bottom and ash hopper.

- New foundations are required for the hoppers, tanks, and silos already described.

- Flue gas ductwork must be installed for the ESP.

- Truck access roads need to be constructed to the ash bins and silos.

For the fuels considered and the units studied, no additional flue gas cleanup was deemed necessary for control of sulfur and nitrogen oxide emissions. However, environmental considerations are very site-specific since they depend on Federal, State, and in some areas local regulatory programs. The emissions control requirements found to be adequate in the present study cannot be generalized.

The following steps are used to estimate derating. First, the boiler efficiencies on oil and CWSF are computed using programs developed for this purpose. The maximum load achievable based on the FEGT is calculated, then the corresponding gas flow rates and temperatures are determined. These are then used to check for possible limits due to erosion by assuming maximum allowable gas velocities of 80 ft/s and 85 ft/s (the method used to calculate these velocities is given later) for the low- and medium-fouling coals, respectively. The gas temperatures previously calculated are used to check for high tube temperatures and other load-limiting factors. The maximum waterwall surface temperature allowed, as it varies with load, is estimated using a correlation developed by CE that takes into account the ash composition and furnace gas temperature. At low loads the gas temperatures are low and the waterwall tubes are relatively cool and clean. With increasing load the ash becomes hot enough to melt and adhere to the walls. The surface temperature rises and can approach the ash fusion temperature under reducing conditions.

The rate of erosion has been shown to be proportional to the amount of abrasive material, such as large particles of silica and alumina, contacting the tube surfaces per unit time (the abrasive mass flux in lb/h-sq ft). This amount of material per unit time is directly related to the percentage ash in the fuel, and to the firing rate, and is the most important parameter causing erosion. The rate of erosion is also dependent on particle velocity, impingement angle, size, shape, hardness, and on tube properties. CE has developed empirical equations for the erosion rate as a multiplicative function of these various factors taken to different exponential powers. Using this equation, the maximum velocity allowable for each coal was back-calculated, allowing the same rate of erosion as is typical of PC-fired boilers. The velocity thus computed is used to calculate the maximum load dictated by the erosion constraint.

There are other factors that could limit the capacity of a boiler. When using CWSF rather than oil, the boiler may experience high desuperheater spray flows, high economizer water outlet temperatures, high tube bank metal temperatures. These conditions are due to the higher gas temperatures (a result of slagging/fouling) and/or higher flue gas flow rates (due to the high water content and high percentage of excess air that coal combustion demands) entering the convective pass. At the same firing rate, CWSF will give an increased flue gas flow and more furnace wall deposition than oil. The deposition causes reduced heat absorption in the furnace radiant section but increased absorption in the convective section. Hence, steam temperatures will typically be higher with CWSF than with oil.

Salient results of the derating study are discussed below. Derating varied from 15 to 60 percent depending on the boiler design and the fuel properties. When firing CWSF made from the low-fouling coal, erosion was the primary load-limiting factor for all four units. With the medium-fouling-tendency coal, fouling (for two of the units) and a combination of fouling and erosion (for the other two) were the primary constraints. The maximum load was on the average 25 percent lower for the coal with greater fouling propensity. With either coal, the tight box configuration exhibited the most derating. A sensitivity study was done on one of the units to gauge the effect on the predicted derating of changes in the magnitude of the assumed values of the following parameters:

- percentage of ash in coal
- weight percentage of coal in slurry
- percentage of excess air

- exponent of velocity term in empirical erosion equation
- fly ash particle size.

Most and least optimistic values of each parameter were used. The variables to which derating was the most sensitive were the velocity term exponent, the fly ash size, and the percentage of ash in the coal. If full variations in all of the parameters are considered, the derating varied from 0 percent to 54 percent. This underscores the limitation of studies like this one. If the parameters above, which concern slurry characteristics and combustion/ash properties, are known in advance, as in the comprehensive DOE-sponsored project already described, the uncertainty in the derating predicted can be greatly reduced.

Conversion Economics

Under the EPRI-sponsored project, CE developed guidelines for evaluating the economic as well as technical feasibility of using CWSF in oil-designed utility boilers (35,36).

The driving force for conversion is the fuel cost differential between oil and CWSF. Other factors that must be considered are the retrofit capital costs, the amount of unit derating, the capacity factor on CWSF and the unit operating MODE. The capacity factor is essentially the extent to which power generation capacity is utilized over a year expressed as a percentage; it is not 100 percent since power demand varies with the time of day and of the year and because CWSF firing alone cannot fulfill peak demand due to derating. Two modes of operation were considered:

1. Fire CWSF all the time, even at peak demand, while using an auxiliary unit such as a residual oil-fired gas turbine at high loads to make up the capacity lost due to derating.
2. Fire CWSF at low demand, but when *high loads cannot* be attained due to derating, fire oil alone.

Although a substantial extra capital cost is incurred in case 1 (in the present study, 32 to 54 percent of the total capital cost) since a turbine has to be purchased, less oil is consumed since CWSF also is fired at peak loads. In case 2, the oil consumption is much greater, since only oil is fired at high loads, while the capital costs are substantially less. A major fraction of the direct costs is related to the ESP. Other contributions are from the ash handling system, boiler modifications, and fuel handling system. For the four units studied, the total capital requirements for case 1 were in the range $92 to 185/kW and for case 2 were $42 to 106/kW. The higher ends of these ranges correspond to those units not having existing ESPs. Flue gas desulfurization was not required for these case studies. Annual operating and maintenance costs include fuel costs, labor, materials, boiler makeup water, water treatment chemicals, and waste disposal. Annual savings in operating and maintenance costs over oil ($6 to 15 million) were greater for case 1 since less oil and more CWSF is used. Levelized cost savings over a 30-year period ($45 to 100 million) were likewise higher for case 1 with all units except the box-type boiler. The latter was so heavily derated on CWSF that the size and capital cost of an auxiliary power generation unit would be prohibitive, and case 2 would be the better choice.

Conversion to CWSF results in cost savings for all four case studies. The impact of levelized (fuel-related) operating and maintenance cost savings is approximately one order of magnitude greater than the levelized retrofitting capital cost. Based on this study, CE developed generalized plots and procedures for determining conversion guidelines. The latter can be used by utility owners to prepare a preliminary economic assessment without going into detail. If the result appears promising, they can request an in-depth analysis for their boiler facility using the coal they propose. A step-by-step numerical example is given in the EPRI report for estimating the levelized annual savings. Figure 30 summarizes the considerations involved in retrofit economics (16, 17, 36). It presents the relationship betwen the payback period over which the conversion cost must be amortized and the differential fuel cost, with the percent derating, oil cost, and capacity factor as the parameters. The payback period decreases with increasing differential fuel cost, increasing oil cost, decreasing capacity factor, and decreasing percent derate.

In an earlier study (37), CE compared the economics of deep cleaning coal to remove sulfur with the alternative expense of a flue gas desulfurization unit. Physical beneficiation by gravity separation is of limited effectiveness since only some of the pyritic sulfur (about 40 to 60 percent of the total sulfur) is removed for some coals, since 90 to 95 percent Btu recovery is normally required. The cost of physical cleaning generally outweighs the benefits gained by the marginal reduction in ash and sulfur. Chemical cleaning, which reduces both the organic and pyritic sulfur, can be a substitute for expensive flue gas scrubbers that became necessary under the 1979 Federal New Source Performance Standards (NSPS) for new coal-fired power plants. However, chemical cleaning is not available commercially at present. With recent progress in genetically engineered sulfur-consuming microbes and other processes, this may change in the near future. In the study described, the break-even costs of deep chemical cleaning were evaluated for two sites. It was found that deep cleaning costs were justifiable whether firing in PC or CWSF form considering the expense (up to 20 percent of the cost of the power plant) incurred in flue gas desulfurization if run-of-mine (ROM) coal were burned instead. Indirect capital savings in furnace design, deslaggers, and the size of the ESP can also be realized through chemical cleaning of the coal to remove organic sulfur, and microcleaning of the fuel to remove inorganic sulfur and finely divided ash.

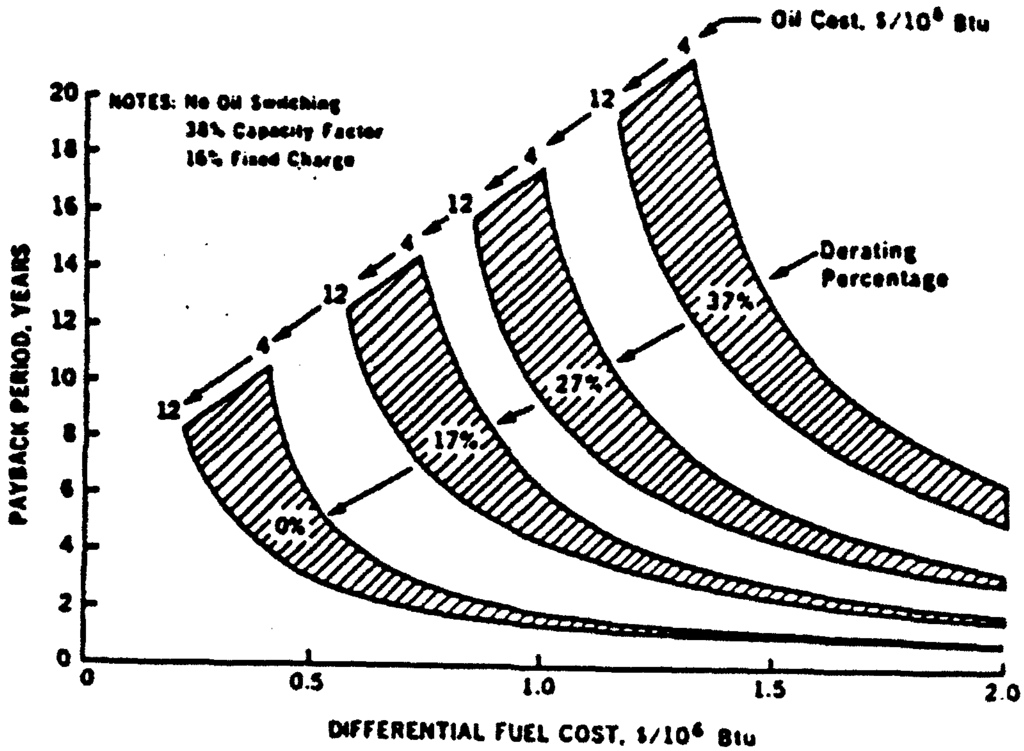


Figure 30. Payback period vs fuel cost and derating.

Carbogel Coal Water Slurry Fuel

In 1974, Scaniainventor, a Scandinavian technology development organization, began work on a CWSF system named Carbogel (1, 7). AB Carbogel works with Berol, an international chemical company specializing in surface and colloid chemistry, and Boliden, an international metals and mining company with expertise in manufacturing and processing. Carbogel has joint ventures in the United States with the Foster Wheeler Energy Corp. and in Japan with JGC Corp. Carbogel can license others to produce CWSF and construct a Carbogel plant. A wide variety of carbonaceous solids can be used as feedstocks, and candidate feedstocks for Carbogel fuel include bituminous and subbituminous coals and petroleum coke. The latter, due to its low volatile matter content, is only usable in gasifiers and injection through the tuyeres of blast furnaces. In contrast, fluidized bed combustors are less sensitive to the feed.

The Carbogel process consists of the following principal elements: coal receiving, storage, and crushing; wet grinding to the proper size distribution; beneficiation by froth flotation for ash and sulfur removal; filtration and dewatering; mixing in the additives; and storage and loading (2, 9). The slurry-making process generally reduces ash to less than 4 percent and sulfur to less than 1 percent by froth flotation. With 50 percent ash removal, the Btu recovery is usually 93 to 98 percent. Solids loadings of as high as 75 percent are possible. Dispersants are used in concentrations of 0.3 to 0.5 percent and other additives amount to less than 0.1 percent by weight of the slurry. Viscosities of typical utility boiler grade fuel measured at shear rates of 50 to 100 s^{-1} fall in the range 1000 to 1500 cp. For low to moderate (400-500 s^{-1}) shear the fuel is pseudoplastic, but at very high shear, it becomes slightly dilatant, especially at 75 to 80 percent coal loading.

The JGC Corp. of Japan and AB Carbogel of Sweden founded a joint venture, Carbogel Japan, Inc., in September 1984 (3). In November 1984, JGC built a CWSF pilot plant, laboratory facility, and CWSF test loops. The 4.5 ton/h capacity pilot plant produces fuel with a coal loading of 70 percent (10). The various steps are described below. Raw coal is crushed, mixed with water, and ground in a primary ball mill. The wet, ground coal is sent over a screen with openings of 200 microns. The underflow is sent to the mixing tank. The overflow is sent to a secondary wet ball mill for fine grinding and returned to the screen to be mixed in appropriate proportions with the coarser coal to attain the target particle size, determined experimentally to yield a high loading and good rheological properties. The fine-plus-coarse mixture is conveyed to the froth flotation circuit and the float is dried to the required level using a vacuum filter. The filter cake is mixed with additives in a kneader (the dispersant used is a nonionic surfactant), and then agitated to give the final Carbogel product. The fuel produced by JGC appeared to have good static stability for over 2 months after production. Its flow behavior was investigated in loop tests. The pressure drops measured were in approximate agreement with those calculated using the correlation applicable to Bingham plastics and using the apparent viscosity measured using a Haake RV12 rotational viscometer, at shear rates corresponding to those in the pipe. The apparent viscosity (from pressure drop measurements) increased slightly after 50 h of continuous pumping in the loop, indicating a possible loss of dynamic stability.

The Foster Wheeler Energy Corp. (FW) has collaborated with AB Carbogel of Sweden over several years to promote and develop Carbogel CWSF. In late 1983, this collaboration resulted in the establishment of Carbogel, Inc., a joint venture company (4, 5). In addition, FW set up a commercial marketing group, Coal Water Fuel Ventures, to produce Carbogel CWSF and promote its sale to utility and industrial clients. Carbogel, Inc., is headquartered on the FW campus in Livingston, NJ, and operates a 1 ton/day batch plant located at the FW research center. Foster Wheeler Coal Water Fuel Ventures, operating under license from Carbogel, Inc., is charged with the commercial development of Carbogel CWSF, including the design and construction of plants, sale and delivery of fuel, and boiler plant conversions.

A CWSF production plant was constructed in Elmwood, TN. The 240,000 bbl/yr (8 ton/h) plant (with a capability of expanding to 10 times this capacity) is owned and operated by a FW subsidiary, Foster Wheeler, Tennessee, Inc. This location offered advantages because of the proximity of coal reserves, existing settling ponds on the site (the plant was formerly a zinc mill [6]), existing two-stage wet ball mills (with a duplicate set available for future expansion), and existing froth flotation cells arranged in multiple cell banks. Centrifugal-type slurry pumps are used for dilute slurries while progressive cavity pumps are used to pump concentrated slurries. The laboratory facilities include low and high shear rate viscometers, for pumping and atomization measurements, respectively, a Coulter Counter, and on-line Micro-Trac for particle size distribution measurement. In-line moisture and density meters are used in the process. Rail sidings, barge loading access, and roads for transportation by truck are available at or near the plant site. For customers situated less than 150 mi from the plant or for low volume users, trucking is the least expensive option; otherwise, barge or rail delivery may be preferred, depending on the handling facilities available at the destination. The unit batching facility at FW's New Jersey location can handle production runs of 1 ton/day. This facility is used to determine the chemical additives package and processing parameters for each feedstock for larger-scale production at the Elmwood plant. As of late 1985 Carbogel was capable of producing 40,000 ton/yr of CWSF in the United States (8). However, due to the soft oil market, it was reported in June 1986 that operations were to be scaled back at FW's CWSF plants in Nottinghamshire, England, and Elmwood, TN. The latter plant was to be mothballed as soon as it had finished filling existing orders for fuel (11).

As previously stated, a wide range of carbonaceous feedstocks has been slurried successfully using the Carbogel process (1, 7, 12, 13, 14, 15, 16, 17, 18) These include U.S. subbituminous and Japanese HVB coals, Philippine's lignite, petroleum coke, asphaltenes, and preparation plant rejects. In a CWSF based on an eastern U.S. bituminous coal, a significant fraction of the cost is attributed to the coal feedstock. In light of the soft oil market, it was believed that if cheaper feedstocks could be applied, CWSFs could be more competitive. Western U.S. coals, besides their lower cost of 1/4 to 1/3 the cost of eastern low sulfur coals on a weight basis account for the majority (83 percent) of the low sulfur coal reserves in the nation. The drawback of these reserves being distant from eastern markets is mitigated if the coals can be slurried and pipelined over long distances. Carbogel succeeded in formulating low rank slurries with loadings in excess of 60 percent by weight of coal, a task made difficult by the low hydrophobicity of low rank coals, by carefully selecting and mixing several additives (total conentration below 0.5 percent by weight) and using no stabilizer. The products were stable and pseudoplastic but even a slight change in the surface characteristics of the feedstock led to an inordinate increase in the consumption of additives. The above approach worked satisfactorily with subbituminous coals, but lignites demanded additive levels that were far too high. The high additives consumption of low rank coals is attributed to high porosity, particularly with the finer fractions (with a higher surface area to weight ratio) used in bimodal particle size distributions. To reduce consumption of dispersants, Carbogel blended a coarse grind of a low rank coal (> 8 percent oxygen by ultimate analysis) with a fines fraction (10 to 20 percent of total coal in the CWSF) composed of somewhat higher rank coal (< 6 percent oxygen). The result was a solids loading well over 60 percent, viscosity of 150 to 250 cP, and 1/2 to 2/3 reduction in the usage of chemicals. In mid-1986, Carbogel, Inc. entered a joint cooperation agreement with the University of North Dakota Energy Research Center (UNDERC) aimed at developing and marketing technologies incorporating low rank coals into CWSF (14). Specifically, UNDERC's hot water drying process for dewatering low rank coals (also termed the hydrothermal treatment process) has by itself—without optimum psd or additives—produced fuels with loadings of 55 to 65 percent solids. It has yielded even higher loadings when combined with Carbogel's standard slurrying procedure (14, 17, 18).

Although the main market for CWSF is expected to be retrofitted oil-designed industrial and later utility boilers, other applications are foreseen. Carbogel CWSF was fed to a Texaco oil-fed gasifier at an ammonia plant in successful demonstrations as early as 1980 (7). This work is now directed toward the use of subbituminous and lignitic coals. In high energy consumption operations such as drying phosphates or aggregates, iron ore pellet induration, and Portland cement manufacture, slurry fuels find ready application in industrial furnaces. In an iron ore pellet sintering furnace in Canada, all 14 burners were converted from oil to Carbogel CWSF. Three thousand tons of fuel were burned during 14 days in late

1985. In its standard 70 percent loading form with a 250 micron top size and additives, Carbogel CWSF can be pipelined, though at lower velocity than used with coarse slurries (ones with a 2.5 mm top size, 50 percent loading, and no additives). However, due to the increased loading, the same amount of coal may be transported. The fuel can then be burned directly without a costly dewatering step. In a novel DOE-funded project, FW studied a slurry-based technological potential of a superfine coal cleaning system. In the process, CWSF is pressurized, heated to supercritical conditions, and rapidly expanded to near atmospheric conditions. The fluid trapped in the pores of the coal explosively changes the coal into a superfine state while leaving the coarser, mineral matter unchanged. The latter can be removed by a cyclone. Seventy-five percent of the mineral matter and 85 percent of the sulfur are removed in the process. Details are presented elsewhere (19).

In the face of current and proposed SOx regulations, back-end or flue gas desulfurization represents a high capital and operating cost for coal-fired power plants, and any means of reducing this expense is welcome. CWSF offers a combination of ways to achieve reductions in sulfur emissions: physical beneficiation (froth flotation) to reduce pyrite, biotechnological and other methods to remove more sulfur (especially the organic portion), in-flame sulfur capture, postcombustion absorption, and finally scrubbers (7, 20). Thus, the most cost-effective sequence may be employed. Limestone has been made part of the slurry matrix with no deterioration of the rheological properties of Carbogel's CWSF. Calcium carbonate with top sizes of 44 and 10 microns were used at a calcium to sulphur ratio of 2:1. A reduction in sulfur dioxide of almost half was noted compared to combustion of undoped slurry. The combustion process was not affected by the presence of the limestone. It appeared that the captor particles were deposited on burning coal particles and that the sulfur reacted with calcium to form sulfide, rather than oxidizing to SO_2. The dispersant used in producing Carbogel CWSF is nonionic and can include SO_x-removing additives. Certain other commercial slurries use ionic dispersion and cannot tolerate addition of sorbents. The rheology of such slurries would be adversely affected.

CBDC Carbogel CWSF

In late 1981, the Cape Breton Development Corporation (CBDC) entered into an agreement with AB Carbogel of Sweden for the design and construction of a CWSF preparation facility in Sydney, Nova Scotia, Canada (21). CBDC later was licensed to produce and market Carbogel CWSF with exclusive rights in eastern Canada (22). Construction began in late 1982 on the 4 tonne/h (4.4 ton/h) pilot plant which was initially to serve as the source of 6000 tonnes (6600 tons) of CWSF for burner evaluation at a utility site in Chatham, New Brunswick. In early 1983, a decision was made to increase the capacity from 4 to 7 tonne/h (7.7 ton/h) since much of the existing equipment was oversized. The CWSF production process is described below (2, 23). Clean coal under 3 mm from a conventional dense medium coal preparation plant, with mineral matter content reduced from 8 to 3 percent, is the feedstock. The pilot plant comprises two stages of grinding; particle size control; two stages of froth flotation, which reduces mineral matter to 1.5 percent; drying in rotary drum vacuum filters; and mixing in additives. The target coal loading of the slurry was 75 percent with viscosity in the 800 to 1,000 cP range. Delivery of the CWSF to Chatham was to be by tanker truck, three trucks a day traveling 750 km (466mi). The CBDC-Carbogel plant is located at CBDC's coal preparation plant in Sydney, Nova Scotia, that receives coal from several mines producing from the Harbor and Hub seams. The metallurgical grade coal being slurried is of HVB "A" and "B" grades with an elevated higher heating value (HHV), low ash, and high sulfur content that is mainly pyritic and amenable to beneficiation. Cleaned coal feed to the Carbogel plant typically contains 4 percent ash and 1.5 percent sulfur, which are reduced during the froth flotation step to 1.6 percent ash and 0.9 percent sulfur (4, 24, 25, 26, 27, 28, 29, 30). The plant was completed in June 1983 and shipments to Chatham began the following month. CWSF was transported 400 mi over a 3- to 4- day run from Sydney to Chatham in 80 tonne rail cars since this mode of transportation was calculated to be less expensive than trucking or barging. Even in freezing weather, the fuel did not cool fast enough to present handling problems during unloading. When severe winter weather set in and the temperature dipped to between 5 °F and -12 °F, insulated rail cars were used and all fuel handling facilities were insulated. A steam line was used to thaw the cars and their fuel outlets. Even when the transit time exceeded 2 weeks due to delays, fuel was easily unloaded in midwinter using a progressive cavity pump assisted by air pressurization of the rail car. Agitation of the fuel in storage was achieved by continuous recirculation. Settling out of coal was not a problem provided a bacteriostat was used to protect the stabilizer. However, removing settled fuel and effectively cleaning empty rail tank cars proved problematical. A high pressure hydraulic flushing procedure combined with agitation and scraping enabled effective cleaning.

As of mid-1986, CBDC had produced over 10,000 tonnes of CWSF, 6000 tonnes of which was for use in Chatham (31). The rest was used in various projects in Canada and abroad. These projects included several combustion tests, burner and atomizer development projects, pumping tests at two locations, use in an iron ore pellet induration furnace, use in an open hearth steel-making furnace, and fluidized bed combustion testing (5, 29, 30, 31, 32, 36). Recent improvements at CBDC include improved mixing with modified high shear rate mixers for improved product quality, replacement of the original two-stage grinding circuit with a cheaper and simpler single-stage ball mill. This mill operated in a closed circuit and used 25 percent less energy, while increasing the capacity of the plant to 6 tonne/h. To date, several coals from the Cape Breton area mines as well as several eastern U.S. coals have been successfully slurried and used. Most of Carbogel's experience in slurrying coals has come with CBDC's bituminous feedstock (12). The CBDC Carbogel plant was recently upgraded to increase storage capacity (29, 31) to supply an ongoing test involving a retrofitted 20 MWe oil-designed utility boiler in Charlottetown, Prince Edward Island, Canada. This project is to use 15,000 tonnes of CBDC-Carbogel (31, 32, 33, 34, 35). As of the end of 1985, EPRI reported that the capacity of the CBDC-Carbogel plant was 40,000 ton/yr (8). The Sydney plant is reported to have been upgraded to a capacity of 8 tonne/h to supply the Charlottetown demonstration (37). Shipments began in September 1986 by the least expensive means of transportation—30-ton tanker trucks.

Rheology and Atomization

FECO (the Forney Engineering Co.), a division of FW in Dallas, TX, operates a piping test loop (two 10-ft sections of 1 in. and 2 in. schedule 40 pipe) to study handling problems associated with slurry fuels (38, 39). The test program began in 1981 on AFT-SOHIO's coal-aqueous mixtures. Progressive cavity pumps proved to be superior to diaphragm and vane pumps.

Carbogel in Sweden operates a 6 ton/h CWSF pilot plant, details of which are given elsewhere (40). An MVB (medium volatile bituminous) Virginia coal containing 6 percent mineral matter and 28 percent volatile matter on a dry basis was milled in the plant circuit, consisting of a primay rod mill and secondary ball mill to a mmd of 44 microns. The original slurry produced had a moisture content of 16.7 percent. This was diluted with deionized water to water contents of 19.4, 22.4, 25.2, 28.2, 30.2, and 32.3 percent. The last one was divided into three portions, two of which were further admixed with just enough stabilizers to attain viscosities corresponding to those of the 22.4 percent and 28.2 percent moisture slurries. In all nine samples, the coal/dispersant ratio was kept constant as was the particle size distribution. A cup and bob viscometer was used to study slurry rheology (instrument and operating details are given elsewhere [40]) and a Malvern 2200 instrument was used to measure the droplet size distribution of the spray produced by a Delavan Airo nozzle, an air-assist internal-mix atomizer, which was modified to reduce fuel pressure and narrow the spray angle to 20 degrees. CWSF viscosity and degree of pseudoplasticity were found to decrease with increasing dilution (water content). As the shear rate was gradually increased from 31 to 450 s^{-1} and then reduced, the initial viscosity was always higher than the final value, indicating that internal structure was being broken down by shearing action and was not being totally reestablished in the final stages of low shear deceleration. At a constant shear rate of 31 s^{-1}, slurries with the lowest moisture contents exhibited the largest drop in viscosity with time, were most thixotropic, over a longer period of time. Moderate shear rate (450 s^{-1}) measurements revealed initial thixotrophy followed by a transition phase of constant viscosity, followed by rheopexy, an increase in viscosity with time. Slurries of water content above 25.2 percent did not exhibit the final rheopectic behavior. The rheopexy observed was believed to be the result of particle sliding, migration, and rotation.

These effects increase with increasing shear rate and increase the inter-particle distance. The water required to fill this space is increasingly scarce at low moisture contents, resulting in rheopectic behavior. Particle size reduction during shear application may also play a role in causing rheopexy.

Atomization experiments indicated, as expected, that droplet volume median diameter (vmd) decreased with increasing moisture content and with increasing A/F. It was found empirically that the vmd was proportional to the slurry viscosity (measured at 450 s^{-1}) raised to the power of 0.3. This exponent increases if slurries with higher solids loading near the critical solids concentration are considered. Slurries containing a stabilizer were more difficult to atomize (higher vmd) than equivalent stabilizer-free fuels. When the moderate-shear viscosity of a coal-water mixture was increased to the same level by either reducing water content or by adding a stabilizer, the latter was more detrimental to atomization quality. It was concluded that, in addition to viscosity, atomizability depends on the type of dispersant and stabilizer present and the moisture content needed to maintain the critical solids concentration (CSC). In the investigation described above, the CSC happened to be 79 percent. It is desirable to have as high a CSC as possible. By approaching the CSC and yet remaining somewhat below it, to ensure low viscosity and pseudoplastic behavior, solids loading can be maximized and the detrimental effects associated with the moisture content of CWSF can be minimized. The CSC is a function of the coal psd, additives used, and the slurrying procedure (30).

Slurry rheology was measured at Carbogel, Inc. using conventional dynamic viscometry (12) from very low through moderate shear and up to high (7000 s^{-1}) shear rate by capillary viscometry. For a typical 72 percent solids Carbogel CWSF, psuedoplastic behavior persisted from low to high shear. Carbogel, Inc. has used the gradual decrease and leveling off of slurry viscosity during the mixing step in processing as a means of verifying optimum particle dispersion. The use of appropriate chemicals has allowed a drastic reduction in the time needed for mixing. Carbogel also studied the rheology and combustion properties of slurries prepared using ionic and nonionic dispersants (12). The former imparts mutual repulsion forces on the surface of coal particles whereas the latter creates dispersion by steric forces. At a shear rate of 100 s^{-1}, the "ionic" slurry with a solids loading of 68 percent had a significantly greater viscosity (1000 cP) than the "nonionic" slurry (700 cP) with an even higher loading of 70 percent. Carbon conversion was higher for the less viscous fuel (as were NOx levels). This is understandable since improved dispersion should lead to improved atomizability. Slurries made using subbituminous coal also exhibited pseudoplastic behavior and behaved similarly to bituminous CWSFs with respect to steric versus charge repulsion. The former case reflected lower viscosity and higher burnout levels, even higher than those noted when burning bituminous CWSFs. In summary of the above discussion, it is believed that:

- The less the mixing needed to effectively disperse the coal particles in a CWSF, the better its quality, atomization, and combustion behavior

- Newtonian high shear rheology is desirable

- Sterically dispersed fuels have potentially better combustion properties than anionically dispersed fuels.

CWSF Burner Development and Testing

The Forney Engineering Company (FECO) has in the past supplied burners for five COM combustion demonstrations in North America and three in Japan (39). FECO, at Dallas, TX, operated an 8-ft diameter cylindrical furnace with water jacket that can be fired at 40 MBtu/h continuously and at 70 MBtu/h for short durations (38, 39). Included in the furnace system is a forced draft (FD) fan with a gas-fired in-line combustion air heater, a steam generator for atomizing steam, air compressor for atomizing air, and an ignitor system that uses No. 2 oil or natural gas.

FECO developed and patented two promising CWSF atomizer designs—the conical Y-jet and the conical internal-mix (CIM) shown in Figures 31 and 32, respectively (38). The Y-jet nozzle operates at a fuel pressure of only 70 psig due to the large annular discharge opening, which serves to minimize potential plugging problems. The conical shape of the end plug allows machining on a lathe rather than requiring precision drilling of exit orifices. Within the nozzle, the fuel flow changes direction gradually to minimize coal particle impact on the passage walls and subsequent erosion. The A/F is comparable to that needed for standard Y-jet nozzles. The spray cone angle is controlled with the angle of the conical plug. The CIM nozzle is similar to the one described above, except that it operates at a higher energy consumption (A/F) since the fuel makes a right-angle turn.

In developing an appropriate burner register, FECO initially tried an existing oil/gas variable flame pattern model. Ignition was difficult and fuel impinged and burned on the side walls. It was believed that the rapid mixing provided by the swirler was chilling the primary burning zone, so the design was altered to permit slower mixing with strong recirculation. Results were still unfavorable and discussions with DOE's PETC led to the addition of a center tube with low air flow. Minimal air flow through this zone led to fast ignition and the desired flame shape. New design conditions were then established:

- Burner throat and air register should be designed with velocities comparable to those found in PC burners rather than oil burners

- The burner should contain two air flow paths with the primary air rotating at low velocity

- The highly swirled secondary air should provide the recirculation zone

- A highly radiant region should be provided at the burner exit.

The patented design shown in Figure 33 provides the duel velocities desired as well as a two-throat configuration to maintain a radiant zone at the burner exit (39). This burner was installed in FECO's test furnace and fired 6000 gal of AFT-SOHIO's coal-aqueous mixture (CAM) through a CIM nozzle, with the following performance:

— 40 MBtu/h capacity
— Combustion air preheat up to 700 °F
— 5 to 10 Mbtu/h gas ignitor input
— 3:1 turndown without support fuel
— Cold furnace lightoff
— 1 to 4 percent oxygen in flue gases
— Controllable flame shape.

Later developments led to carbon conversion levels in the 96 to 99 percent range, air preheat of only 250 °F, and a 4:1 turndown (41).

AGRICO Chemical Co. of Pierce, FL, operates rotary phosphate rock dryers to produce 800 tons/h of dry product. The dryers are normally fired on No. 6 oil using two Ray rotary cup burners providing a total heat input of 90 MBtu/h. In April 1983, CoaLiquid, Inc. test burned their coal-oil-water fuel (consisting of 50 percent coal, 40 percent oil, 10 percent water, and no additives since stabilization is by ultrasonics) in one of AGRICO's 200 ton/h dryers over 3 days. Beginning in January 1984, coal-water fuel (COWF) was used in a 300 ton/h dryer and over half a million gallons had been used by mid-1984 (5, 42). The new fuel delivery system was designed and installed by CoaLiquid. No. 6 oil burning capacity was retained so that two fuels could be fired. A single low-pressure, stainless-steel, air-atomized, dual-fuel Forney-Verloop burner (shown in Figure 34) was used and lasted for over 4 months and 300,000 gal of COWF. No. 6 oil is delivered to the burner at 20 to 30 psig while COWF is delivered at 50 to 65 psig and 250 to 265 °F. Combustion air is pulled through the furnace by an induced draft (ID) fan.

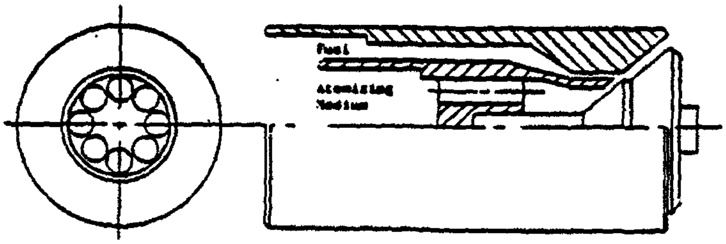


Figure 31. Forney conical y-jet atomizer.

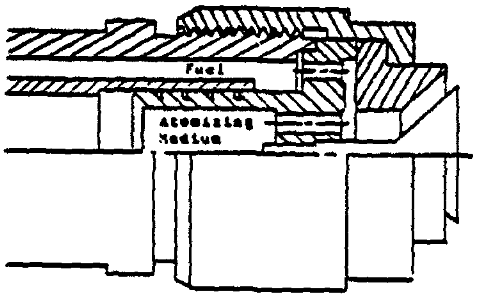


Figure 32. Forney conical internal-mix atomizer.

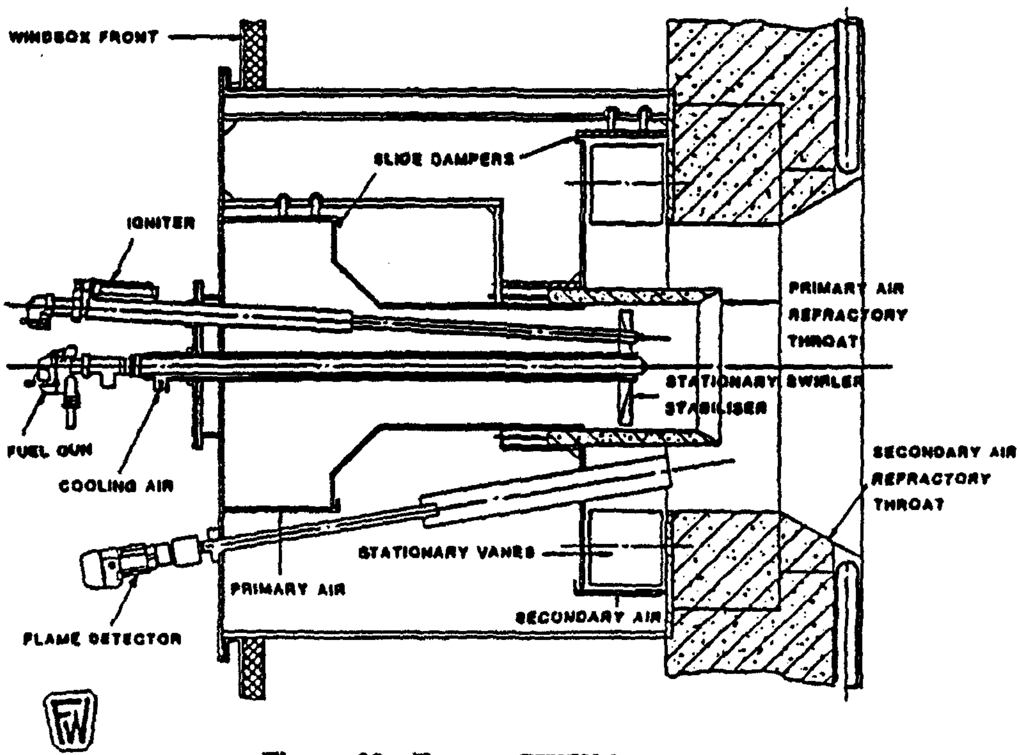


Figure 33. Forney CWSF burner.

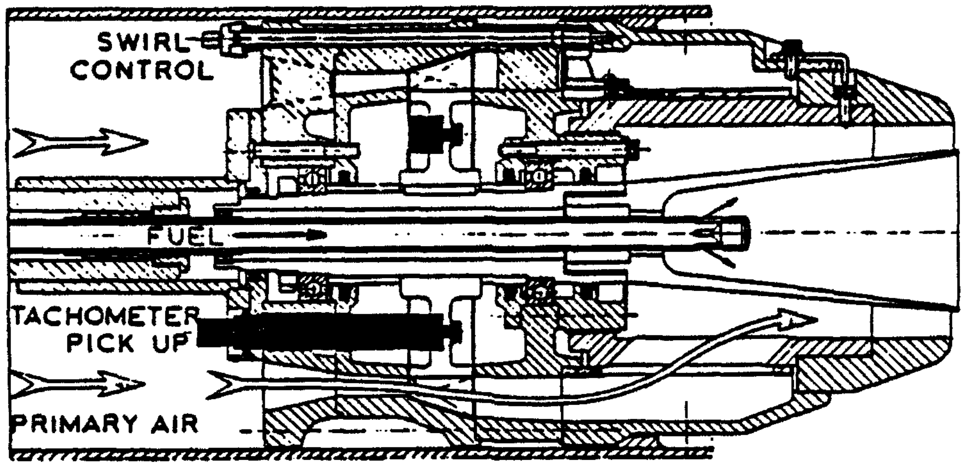


Figure 34. Forney-Verloop COWF burner.

Foster Wheeler Power Products Ltd. of London, England, operates a horizontal, multifuel, cylindrical (CWSF/oil/natural gas) 300-kW, water-jacketed test-firing rig (43, 44). A convective fouling section, comprised of air-cooled tubes (the geometry of the tube bank can be varied to reflect the convection section of various boiler types) and viewing and sampling ports is provided. Other components include a long-cone, high-efficiency cyclone, FD and ID fans, fuel handling equipment, exhaust ducting, and a stack. On CWSF, the rig is operated without support fuel or air preheat. Flames are not very luminous and exhibit an abundance of sparklers. For the fouling studies described below, the flue gas temperature at the inlet to the fouling test section was 1050 to 1150 °C. CWSFs made from the same English HVB coal, in both beneficiated and unbeneficiated form, using either sodium-based or ammonia-based additives were tested. The extent of fouling (the amount of deposition over a given period of time) was greater for unbeneficiated CWSFs and those including sodium-based, compared to ammonia-based, additives. Nevertheless, deposits were easily removable in all cases. Although the beneficiation step resulted in lower ash content, sodium and iron levels were slightly raised. Still, the beneficial effect of the former dominated the detrimental effect of the latter. In some cases, fly ash was larger than the top size of coal in the CWSF, indicating that some ash agglomeration had occurred. NOx levels were low, even for the CWSF containing an ammonia-based dispersant.

In Sweden, AB Cargobel has tested various burner prototypes with capacities up to 3.5 MW (45). Atomization is based on the rotating cup approach, which uses low slurry velocities. This approach was found to be too complex and difficult to scale, so currently they concentrate on using a conventional internal-mix single-orifice atomizer (36, 46, 47), with critical wear parts made of tungsten carbide. Spray quality (droplet mmd and weight percent of droplets over 250 microns) was determined by laser diffraction and found to be satisfactory. Three commercially available oil burner registers, representative of designs used in utilities, industry, and central heating were modified to different extents and matched with the nozzle mentioned above. The modified burners incorporate two to three air zones and a divergent refractory quarl. They range in capacity from 7.5 to 35 MBtu/h. Burner testing at partial loads in flame tunnels revealed carbon conversion of 98 to 99.8 percent using neither support fuel nor combustion air preheat (excess air requirements varied depending on the burner but were acceptable; A/F varied from 0.2 to 0.3), and is a unique achievement. Cold furnace lightoff of CWSF was attained, with the oil support being removed after a few minutes of use. Carbogel intends to commercialize an optimum burner design. Details of Carbogel's burner development work are given elsewhere (36).

Burner Development for the Chatham Demonstration

In mid-1982, a contract was awarded to FW Canada, Ltd. for the development of CWSF burners for the conversion of a utility boiler in eastern Canada. The Chatham Unit No. 1 in New Brunswick is a 12.5-MWe, A-frame, front-wall fired, 1940's Foster-Wheeler, no reheat, balanced draft boiler that was originally designed to fire New Brunswick coal but was converted to firing No. 6 fuel oil in the early 1960's (22). It was used to conduct a COM combustion demonstration in 1977-80 (24). The boiler produces 139,700 lb/h steam of 605 psia and 835 °F. Ignition of the four burners was based on the design shown in Figure 3 for use at Chatham (22, 39, 41). The new burners (see Figure 35) are rated at 40 gigajoules per hour (GJ/h) (38 MBtu/h) with ignition and support energy available from two light oil pilots of about 6 GJ/h (5.7 MBtu/h) capacity at each burner (24, 25, 26). They were designed to be flexible to allow optimization in the field. The position of the following parts were adjustable: inner throat, swirler, fuel gun, ignitor and high energy spark ignitor. The burner was designed to fire heavy oil by changing the nozzle and the position of the primary air damper. The nozzle used was the conical internal-mix design.

The Chatham Utility Boiler Demonstration

The burners described under the previous subheading were fabricated by FW of Canada and tested by FECO of Dallas. For testing purposes, at a time when the CBDC Carbogel plant was undergoing construction, 550 tonnes of CBDC coal were sent to AB Carbogel in Sweden for slurrying, and the product was shipped back to North America (22). For actual testing at Chatham, the FW Energy Corp. of Livingston, NJ, developed the boiler test program and provided supervision and analysis of the results. The FW Development Corp. provided analysis of the fuel and of the ash deposits (26). Foster Wheeler Limited of St. Catharines, Ontario, Canada, was responsible for the overall project management, detail engineering, and burner fabrication.

To prepare for testing, FW inspected the demonstration boiler at Chatham. Air infiltration through the boiler casing was minimized by replacing the insulation and refractory wherever needed. The boiler and air heater gas passes were cleaned of debris (24, 25). Four new burner windbox assemblies were installed. Modifications to the front wall and to combustion air ducting to the burners were made. Five waterwall tubes were replaced to accommodate the larger burner throats. Brickwork and refractory around the throats were also modified. Full load on CWSF was deemed to be 10 MWe of output (20 percent lower than on the design fuel) (5, 27). By early 1984, baseline tests on oil were done at 50, 70, and 100 percent load (24, 25). The boiler was also operated at full load on CWSF without support fuel. Lightoff on CWSF proved to be straightforward and repeatable using only one of the two pilots provided. This pilot was likewise sufficient for low load support (26). Stable flames were achieved at the same excess air levels used with PC. Switching back and forth between CWSF and oil was done rapidly and without difficulty by changing the nozzle and the position of the primary air damper (took less than 15 minutes per burner during continuous boiler operation). Seven different wear-resistant atomizer materials (hardened tool steel, tungsten carbide spray coating, boron heat treatment on tool steel, cemented tungsten carbide, and three ceramic materials) were tested for periods of up to 125 h and a combination of cemented tungsten carbide and hardened tool steel was chosen (28). Testing in Chatham ended in December 1984; salient results follow (28, 31). Normal boiler start-up consisted of lightoff with No. 2 oil, warmup, switch to bunker oil to bring steam production to operating level, and switch one burner at a time to CWSF. It was also possible to light off the boiler on CWSF without the warming step using No. 6 fuel oil, and using one of the two lighters provided on each burner. Fuel viscosity varied from 500 to 1200 cP. Atomizing air pressures below 116 psig were used satisfactorily. Steam atomization was attempted and found to be unsuccessful with CWSF. The ash formed was light, fluffy, and did not deposit on the furnace bottom or in the cyclones. On No. 6 oil, the average boiler efficiency was 84 percent while on CWSF the average was 78 percent; and the maximum attained was 81 percent. The poorer efficiency was largely due to unburned combustibles and to a smaller extent, higher moisture losses. Burner turndown attained is reported to be 5:1 (48).

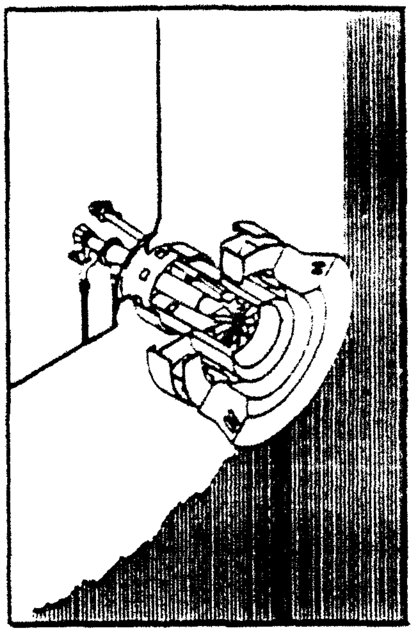


Figure 35. Thirty-eight MBtu/h Forney CWSF burner.

EPRI-Sponsored Utility Scale Burner Demonstration

As a prelude to the EPRI test, FW converted their own 50,000 lb/h boiler in New York as a burner development test site. FW's entry in EPRI's demonstration of large commercial CWSF burners consisted of a 100 MBtu/h unit to be fired in an industrial watertube boiler (8, 47, 48, 49, 50, 51) The unit is a single-burner, Wicks "A" package boiler, rated at 200,000 lb/h and is located in the Allison Gas Turbine Plant of General Motors Co. in Indianapolis, IN. Both air and steam atomization were to be attempted and 250 tons each of ARC-COAL (the reference fuel) and Carbogel CWSF from FW's Elmwood, TN, plant were to be burned. The fuel was to be delivered to the boiler plant by rail tank car, heated to 80 to 90 °F, and fired with combustion air heated to 300 to 600 °F. Shakedown tests began in August 1986 but work stopped for two reasons. Due to the depressed cost of petroleum, slurry-making economics were unfavorable, and FW in Tennessee and the Atlantic Research Co. no longer produced slurry fuels in quantities sufficient for the demonstration. Also, slurry stability problems (sedimentation occurred during pumping) were too severe to permit continuation of the demonstration. These problems were attributed to inexperience in preparing and handling a slurry made with a new coal feedstock. Installation of the CWSF burner and testing of feed lines have been completed, but the boiler was firing fuel oil at last report (51).

Boiler Conversion and Derating Studies

FW Power Products of London, England, performed a preliminary study for the conversion of three sizes of oil-fired industrial boilers to CWSF. The units ranged in capacity from 14 to 68 tonne/h of steam (52). Existing oil storage tanks may be appropriate for CWSF storage provided they are cleaned. The energy density of CWSF is about 30 GJ/m^3 versus 41 GJ/m^3 for oil. Hence, additional storage capacity may be required, particularly if the oil firing option is to be retained. Though the static stability of CWSF during storage is usually of adequate duration, a low speed impeller can be used to prevent settling over extended periods of time. Unlike heavy oil, CWSF is pumpable at ambient temperature and no heating is required unless subfreezing temperatures are expected. Positive displacement pumps are preferable to other types since they operate at low shear rates; high shear has been shown to adversely affect slurry properties. As a rule of thumb, the pump is sized twice as big as it needs to be. Pump construction materials are discussed elsewhere (52). The pipes are sized to keep velocity in the 0.2 to 1.0 m/s range. Long-radius bends, not elbows, are used to minimize erosion. Since CWSF is not corrosive (pH is usually near neutral), carbon steel piping suffices. Air preheating can be by the less expensive direct firing of natural gas in the air-carrying duct (after the FD fan and before the windbox) to attain a temperature of 100-150 °C, since this results in only a small decrease in the concentration of oxygen in the combustion air.

For the three boiler conversion case studies considered, the derating varied from none to 40 percent. The former corresponds to older, conservatively-designed (liberally-sized) boilers while the latter is more typical of newer units. The FEGT and the gas velocity in the convective sections (passes) of the boiler had to be lowered to acceptable levels (1000 °C and 20 m/s) by firing at a lower rate. Design details of the three boilers evaluated are given elsewhere (52).

Conversion Economics

In a study conducted by Carbogel, Inc. (53) three generic categories of boilers were assessed for conversion costs. Coal-designed units would cost $100 to 125/kW to convert while coal-capable/oil-gas-designed units would cost $175 to 200kW. A step-by-step procedure for calculating the payback period and the benefit to cost ratio is given and is applied to a case study involving a 100 MW boiler. Assuming no derating, which would otherwise also have to be included in the calculations (30), and a 70 percent capacity factor, results are payback period versus the fuel cost differential ($/MBtu) with a series of lines for the conversion cost ($/kW). Evidently, the payback period increases with conversion cost and with decreasing fuel cost differential.

Carbogel, Inc. conducted a study of the relative economics of a plant having coal cleaning facitities and those needed for CWSF production (to which ROM coal is delivered by rail) versus one that is supplied with washed coal from a mine-mouth washery. Plant sizes of 770,000 ton/yr and 2,750,000 ton/yr were considered (2). The cost of coal and transportation costs had a major effect on delivered CWSF cost. A more recent study by Carbogel, Inc. centered on an assumed plant size of 1,500,000 ton/yr dedicated to providing five industrial users generating about 675,000 lb/h of steam each, demonstrating that larger plants benefit from economies of scale. Calculations indicated a plant capital cost of $75 million (53).

7 OTHER BURNER MANUFACTURERS

PETC Rotary Cup Burner

The Pittsburgh Energy Technology Center (PETC) in conjunction with Gilbert-Commonwealth, Inc., has developed a rotary cup CWSF burner that has been patented with the DOE as assignee and is available for licensing (1, 2, 3). This burner has been tested at PETC in a 100 hp firetube industrial boiler and is shown in Figure 36 (1). It consists of an air register with a center air tube, a rotating cup, a fuel delivery tube, and a variable speed AC motor with accompanying controller to drive the rotary cup. CWSF combustion without natural gas support was achieved using a 15 degree cup angle, an added refractory ring, 4,000 rpm cup speed, 10 to 15 percent excess air, and 530 °F secondary air preheat. A small amount of steam was introduced through the annular space shown in Figure 36 to prevent rapid drying of the slurry before it left the cup. Firing rates of up to 4.6 Mbtu/h were attempted. Fuel pressure at the burner averaged only 25 psig. However, carbon conversion percentages averaged in the low eighties. This still compared favorably with the performance noted with an internal mix atomizer. Better performance is expected in larger boilers with a lower volumetric heat liberation rate.

The Lezzon Group

The Lezzon nozzle concept was developed by the Lezzon Group in Manchester, NH, and GIMRET International, Inc. of Shrewsbury, MA (4). As shown in Figure 37 (5, 6), it produces a thin low-velocity conically-diverging CWSF sheet which is broken up under pressure by the shearing action of two annular air flows in the same direction on both sides of the fuel film. The thickness of the annular liquid sheets, SL1, is minimized while considering the top size of the coal constituting the CWSF. Atomization mainly occurs internally within the elongated throat, and droplets are expelled via an annular exit in a hollow conical pattern. No fluid swirl is used and there is no mixing chamber as there is in the T-jet design. Cooling air exits by the annular opening shown and serves to cool the heat shield, which is exposed to radiative heat sources. The Lezzon nozzle is designed to allow some important adjustments. The widths of the fuel annulus and of the exit annulus, the latter being common to the fuel and the air, are adjustable.

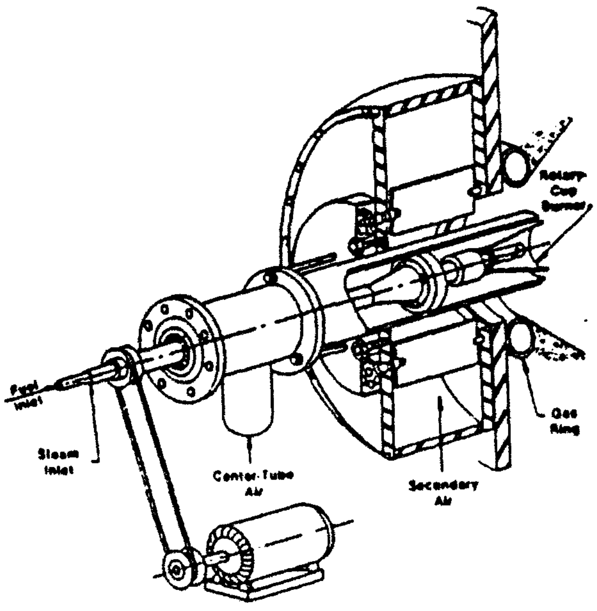
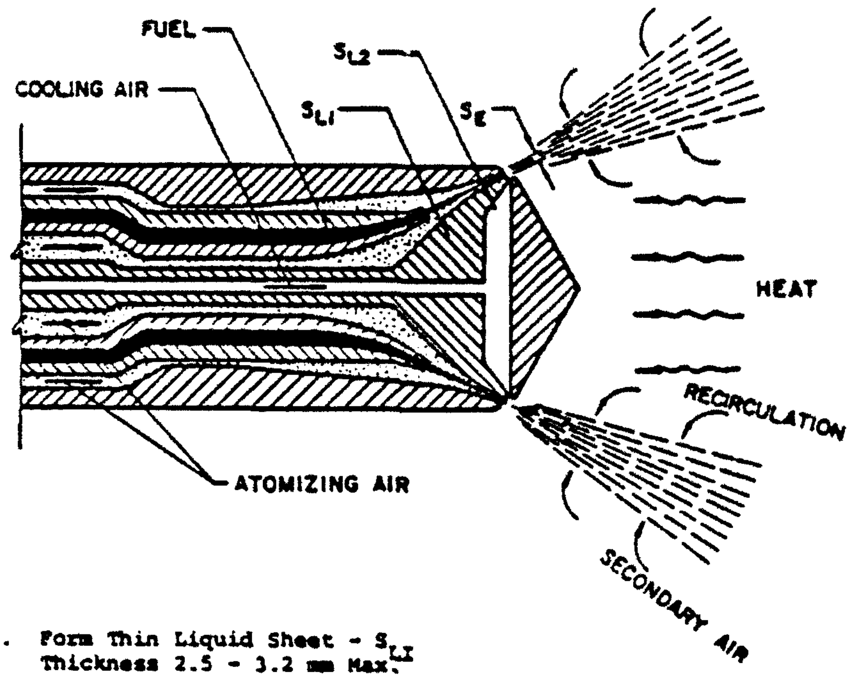


Figure 36. Rotary cup burner and air register arrangement.



1. Form Thin Liquid Sheet - S_{LI}
   Thickness 2.5 - 3.2 mm Max.

2. Sheet Thins in Conical Flow - S_{L2}

3. Two Air Annuli - Common Flow Channel

4. Atomize at Elongated Throat

5. Gas Throat Width: S_T S_E - S_{L2}

Figure 37. Lezzon CWSF nozzle.

The relative flow of air to the inner and outer air annuli can also be varied. The spray angle can be changed by changing the tip portion. The Lezzon nozzle is designed to work at modest air pressures (e.g., 60 psig) and may exhibit good abrasion resistance due to low liquid velocity and the absence of eddies and swirls within the nozzle. Only the tip portion need be fabricated from hardened materials. The avoidance of small openings precludes plugging, and even if plugging occurs, a simple on site adjustment to increase the width of the fuel orifice should dislodge the particles. Using cooling air along with an insulating material for the heat shield is expected to eliminate coking of coal particles at the nozzle exit.

A Lezzon nozzle prototype was tested at the Centre for Energy Studies of the Technical University of Nova Scotia in Febuary 1984 (7). Initial tests with water at 20 and 56 psig verified desirable spray pattern. A 3:1 turndown was achieved with heavy fuel oil. With coal-oil-water mixture heated to 90 to 100 °C, a stable flame was attained with a 3:1 turndown. At a CWSF firing rate of about 10 lb/min, excess air levels of less than 20 percent were adequate. A 3:1 turndown was attained with little visible erosion after 3 hours of operation. Deposits formed on the heat shield did not block the flow of CWSF and were easily removed. Optimum operating conditions on CWSF were air pressure of 30 psig, fuel pressure of 42 psig, excess air below 20 percent, and 450 °F secondary air preheat with intermediate swirl. No nozzle plugging was observed. Problems with occasional O-ring failure and eccentricity of the annular discharge aperture causing an unsymmetrical spray pattern were believed to be easily corrected.

Testing of the Lezzon nozzle using a cellulose gum-water solution (8) revealed that the critical nozzle dimensions which most influenced the spray quality were the fuel annulus gap and the spray discharge gap. A fine spray was produced when these gaps were set to 0.5 mm. Secondary air swirl was found to enhance atomization quality and decrease atomizing air requirements.

Parker-Hannifin Corp., Gas Turbine Fuel Systems Division

In 1983, Parker-Hannifin Corporation (PH) acquired exclusive rights to the balanced-swirl spray nozzle and mixing device which has since been manufactured and sold by their Gas Turbine Fuel Systems Div. in Cleveland, OH (9). The principle involves opposing (counter-swirling) vortices which are produced in two different fluids (e.g., compressed air and CWSF) in adjacent chambers of the device. Fluid from one chamber enters the other and mixes with the second fluid. The mixture then leaves this chamber. Atomization is only one of the possible applications for this concept.

Pressure-atomization, as used with light liquid fuels, is not effective with CWSFs due to their high viscosity (10). However, in typical twin-fluid internal-mix nozzles, the coal particles are accelerated by the atomizing medium and cause erosion of the passages constituting the mixing region. Atomization fineness has been related quantitatively to the thickness, diameter, etc, of the liquid sheet at the point of atomization. In air-blast atomizers used in gas turbines, the fuel is spread into a thin film using an air stream and the film is then broken up by another air stream. Combining fluid swirl (to improve mixing) with the thin film concept led to an improved CWSF nozzle design at PH, called the DBS. As shown in Figure 38 (10), CWSF is pumped into swirl chamber "A" through tangentially-inclined ports to create a vortex such that slurry issues from lips "B" as a thin film at low velocity. Compressed air is fed into chamber "C" to create a strongly swirling flow which shears the slurry film, causing it to break up into a fine spray. This spray is conical in form and the droplets do not contact metal, thereby minimizing erosion. Atomization quality (using water and conventional liquid fuels) was better than that obtained with standard gas turbine nozzles.

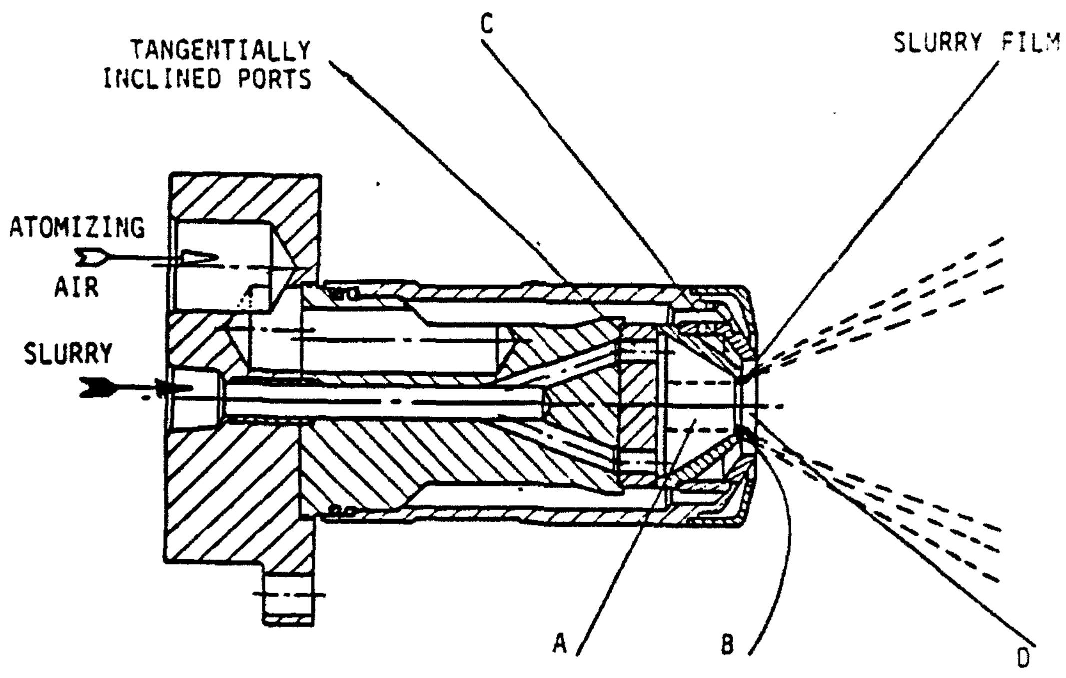


Figure 38. Parker-Hannifin DBS nozzle.

PH has supplied DBS nozzles to DOE's Morgantown Energy Technology Center (METC) and PETC as well as several gas turbine and boiler manufacturers for testing. Slurries with viscosities in the 300 to 2500 cP range have been atomized. With a very high CWSF viscosity, it may become difficult to generate a vortex in the fuel swirl chamber and so a modified design, the VIP, was developed to ensure that the slurry is formed into a thin, cylindrical film even if a vortex is not formed. As shown in Figure 39 (11), atomizing air is supplied on both sides of this film and it is reported that slurries of viscosities up to 2200 cP can be accommodated.

The company has supplied prototype designs to more than a dozen research organizations, with nozzle capacities ranging from 100 to 13,000 lb/h (12). The design philosophy behind the PH nozzles is to use low fuel velocities due to the abrasiveness of CWSF, and the application of external mixing of the fuel film and the high velocity atomizing medium. The slurry discharge annulus is sized to be several times the dimension of the largest coal/impurity particle expected, for clog-resistance. The spray angle of the PH nozzles may be adjusted by changing the tips. The DBS design operating on CWSF has yielded a spray with a volume median droplet diameter of only 75 microns, when the constituent coal had a vmd of 30 microns. This was achieved with an air pressure of only 20 psig (12).

Few problems have been noted with the CWSF nozzles. Wear has been minimal in the slurry passages, but some has been observed in the atomizing medium passages, and so new materials are being tried. Where slurry fuel passage clogging was observed, the clearance was simply increased. PH's promotional literature (13) lists three commercially available CWSF nozzle designs: balanced swirl (DBS), high viscosity (viscosity insensitive prefilmer [VIP]), and dual fuel (coal-slurry-gas [CSG]). The latter is similar to the DBS or VIP concepts with added orifices through which natural gas can be fired. Nozzle tips are interchangeable to allow matching the spray pattern to the burner air flow characteristics (13, 14).

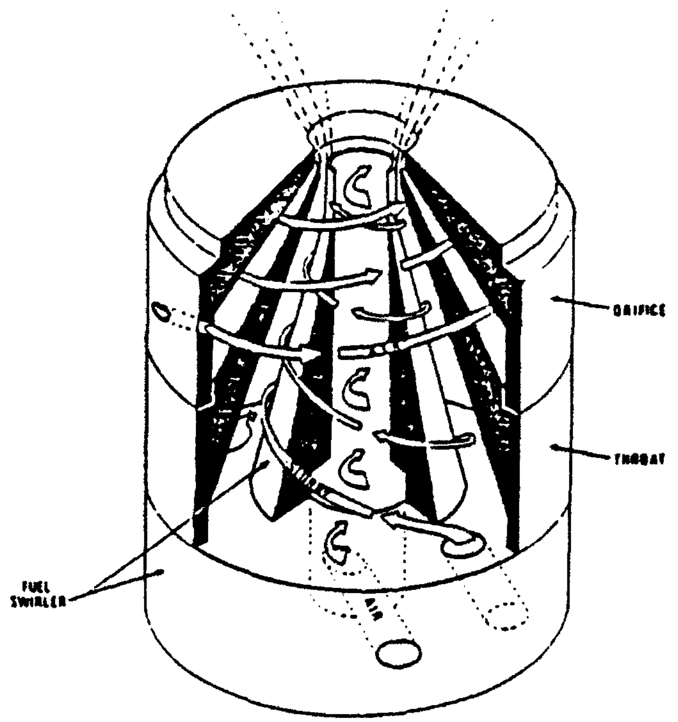


Figure 39. Parker-Hannifin VIP nozzle.

Various nozzle mounting configurations are possible. The literature depicts four ways of introducing the fluids into the nozzle. The VIP design has found successful application in atomizing CWSF, micronized CWSF, petroleum-coke-oil mixture (PETCOM), and petroleum-coke-water mixture by several Government and private research organizations, university laboratories, slurry makers, and gas turbine and boiler manufacturers for testing and use (15). The nozzles built have been as large as 13,000 lb/h and atomizing air at 90 psig and 100° F is typically specified (16). A/F ratios of 0.4-0.5 are typically mentioned. Though this is high compared to internal-mix nozzles used in boiler practice, gas turbine nozzles generally use relatively high A/F levels (10).

The atomization of ARC-COAL CWSF (70 percent coal loading with viscosity in the 750 to 1000 cP range) was studied at Carnegie-Mellon University (CMU) using a VIP nozzle (11). A description of the atomization process follows. CWSF exits the nozzle as a thin swirling sheet sandwiched between two air streams. Atomizing air is divided between core air, swirling in the same direction as the slurry and the bulk of the air, which exits as a high-velocity counterswirling stream through the outer annulus. Interaction between the slurry film and the outer air stream generates high shear, the sheet develops instabilities, and atomization results. The tip of the nozzle used was fabricated from 440-C stainless steel and, due to the low slurry velocities (< 10 ft/s), erosion is not a significant problem. The 500 lb/h CWSF nozzle was operated using 175 psig air. The spray angle was found to decrease significantly with increasing air pressure, and regular, rapid pulsations in the slurry flow were detected. The latter might have detrimental effects on flame stability (11). Average droplet velocities were 40 to 80 m/s. Other workers have noted that secondary air swirl can have beneficial effects on the atomization quality derived from the VIP nozzle (17). In further atomizer testing conducted at CMU, a revised 600 lb/h capacity nozzle (with atomizing air requirements reduced from 175 psig to 90 psig) was employed. At design conditions of nozzle operation, the liquid sheet was found to break up immediately at the atomizer exit (18) as depicted in Figure 40. The CWSF used in testing was ARC-COAL with 70 percent coal loading by weight, 850 microns top size, vmd of 19 microns, and viscosity in the 500 to 750 cP range. The fuel annulus gap sizes were 0.04 and 0.06 in. (1 and 1.5 mm). Ligaments up to a centimeter long were observed using still photography at A/F ratios < 0.3, but were fewer in number at higher A/F ratios. Slurry vmd's were in the 55 to 66 microns range (this being two to four times the vmd of the constituent coal). An interesting observation relates to the spatial variation in droplet size. There was a preponderance of small droplets at the center of the spray while larger ones were observed at the edges. Droplet vmd increased linearly with distance downstream of the nozzle. No erosive wear of the nozzle was noticed over the course of testing. When the nozzle was operated at one-third of its design capacity with very high A/F ratios of 1.2 to 1.5, the droplet vmd's were substantially reduced (19). Photography was useful in establishing that under any operating conditions, many droplets existed that were beyond the detection limit of the Malvern droplet-sizing instrument used. Two correlations were developed to describe the Sauter median diameter (smd) of the spray as a function of A/F ratio (with other parameters held fixed). Some of the nozzle characteristics at CMU were verified during in-house testing by PH in their atomizer test facility (20). PH also operates an erosion testing rig that is used to determine wear rates of the slurry passages and accelerated wear rates using periodic injection of alumina grit ino the high-velocity air-conveying passages (this being the area in the nozzle that is most susceptible to wear if contaminated air or steam is used). Preliminary tests have indicated that ceramics give better resistance than the standard, hardened 440-C stainless steel. Lignite-water slurry was atomized using the VIP nozzle and showed the usual hollow conical spray pattern (21). For a slurry with a coal vmd of 39 microns, droplet vmd's of 60 and 90 microns were observed at A/F ratios of 1.0 and 0.5, respectively. Similar good atomization was noted in other work on lignite-water slurry (58 percent loading) atomization (22). PH has conducted test-firings of CWSFs using its nozzles at the Centre for Energy Studies of the Technical University of Nova Scotia (23).

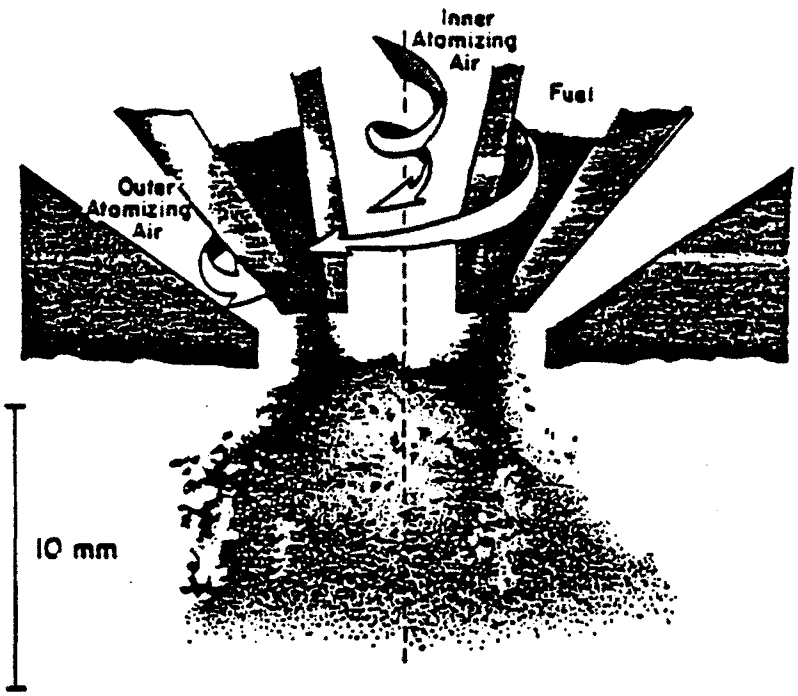


Figure 40. Atomization by the VIP nozzle.

Coen Company, Inc.

COM and early CWSF combustion testing at DOE's PETC was conducted with modified oil-designed Coen nozzles and modified Coen air registers (24, 25, 26, 27). Modifications made included enlargement of the fuel passages to halve the fuel velocity and reduce the pressure drop, reduction of the spray angle from 75 to 60 degrees to allow retraction of the nozzle (and increase residence time), and alteration of the dual-air-zone register to allow high swirl of the outer flow and strong recirculation of hot products of combustion. CWSF was combusted in PETC's 700 hp watertube boiler with 500 °F air preheat and no support fuel firing. Various wear-resistant nozzle materials were tested and tungsten carbide was found to be superior to tool steel and stainless steel when atomizing either COM or CWSF. The Coen #1MV nozzle shown in Figure 41 (26) operates at 150 psig of fuel and atomizing air. The fuel and air streams flow coaxially into the internal-mix nozzle. In the mixing area the slurry spreads radially across a plate and is broken up at the edges of the plate by 12 streams of atomizing air. The air-slurry mixture then flows into a chamber and out through seven 5/32-in. holes in the end cap. The atomizer is fabricated from carbon steel with tungsten carbide sleeve inserts forming the orifices in the end cap. Spray geometry is determined by the number, size, and location of holes in the interchangeable end cap. This nozzle bears some similarity to the B&W T-jet described in Chapter 4.

Coen conducted a development program to produce a burner/atomizer design dedicated to CWSF (28). A two-dimensional computer model, called the DAF (distributed air flow) model, was developed to describe near-burner aerodynamics and optimize the register. It consists of an adjustable primary (core) air spinner with a 6:1 swirl adjustment which induces the recirculation of hot combustion gases. Secondary (annular) air is swirled through adjustable louvers and enters the furnace through a refractory divergent throat (see Figure 42) (28). A newly-designed 6-hole nozzle (model CWA) was developed to handle both CWSF and heavy fuel oil (29). Atomization is by a two-stage, low-velocity concept. Low-velocity CWSF is distributed to a high-velocity jet of atomizing fluid in the first stage. The mixture passes through a replaceable ceramic button and is then mixed with air or steam in the second stage in a manner that reduces jet velocity while allowing rapid expansion of the jet. Thus, particle velocities are

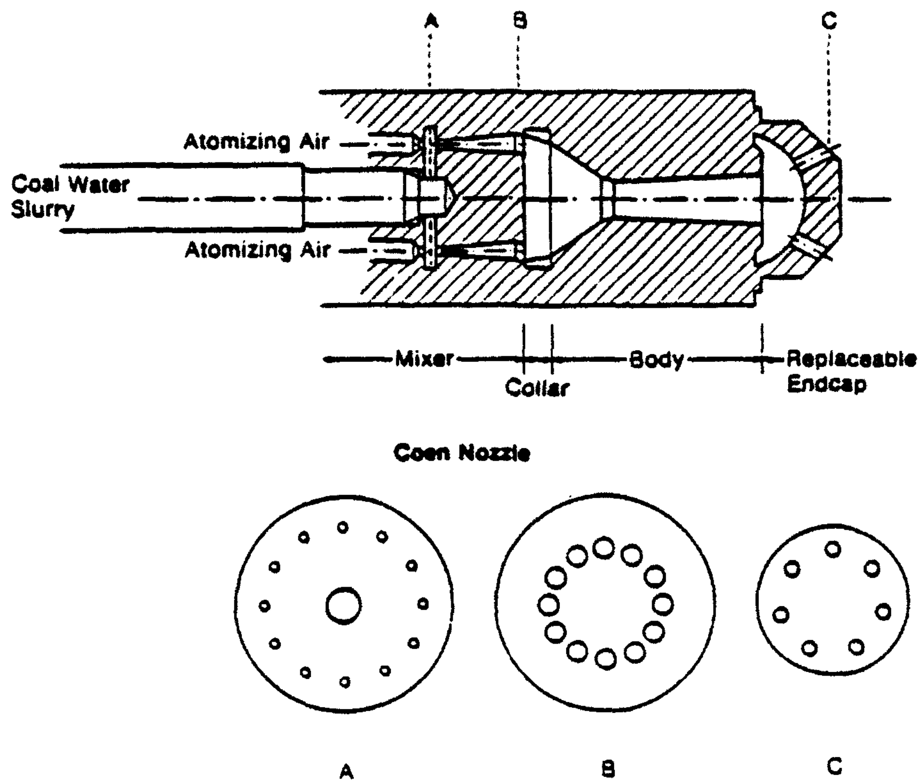


Figure 41. Coen #1MV atomizer.

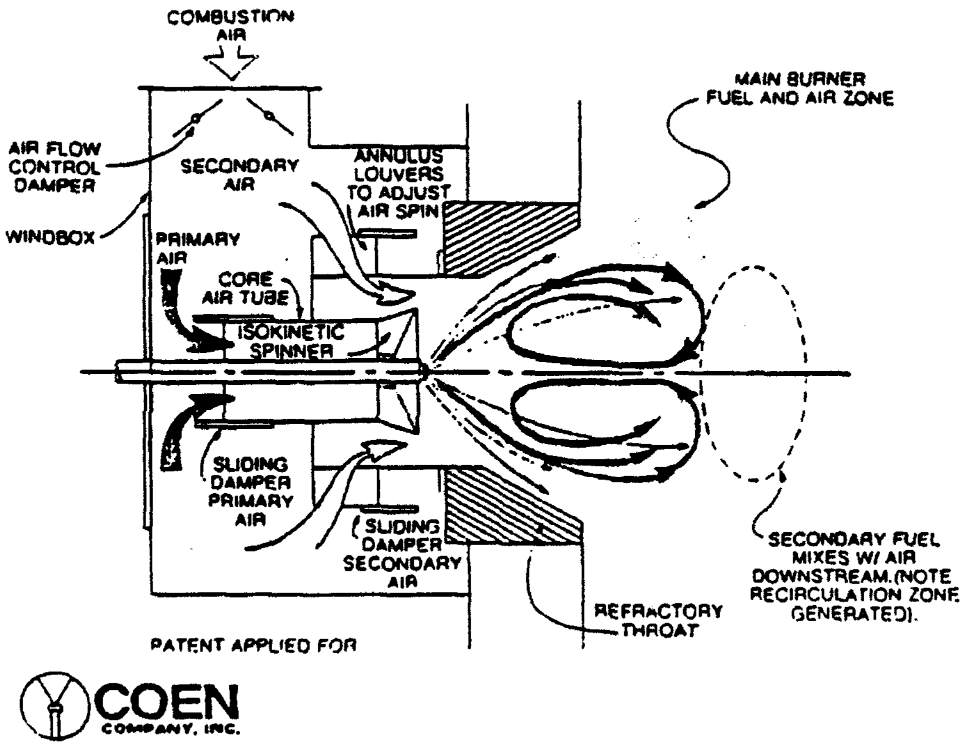


Figure 42. Coen Type DAF burner.

much lower than with other internal-mix CWSF nozzles. This increases the residence time of droplets in the burner throat and enhances flame stability. Burner performance characteristics are reported to be fuel at 100 psig, 50 psig atomizing air, A/F = 0.2, no preheat necessary for slurry or atomizing air, nozzle life of 6 months or 4400 h (low velocities in slurry-wetted parts), 6:1 turndown, 400 °F combustion air preheat and no support fuel (alternatively, unheated combustion air with 5 to 8 percent gas support), Δ Pwf < 4 in. water, low excess air requirement, carbon burnout similar to PC levels, and nozzle able for firing other liquid fuels (28).

In a demonstration firing of CWSF in Boston Edison's 135 MW (935,000 lb/h of steam) Boston Mystic 4 unit, a CE tangentially-fired boiler, in late 1984, two of 24 oil guns were replaced with Coen model 2MV CWSF atomizers, supplying 6 percent of total heat input, rated at 35 MBtu/h each (3500 lb/h, 5.8 gpm) (30, 31, 32, 33, 34). Coen's air atomizers were selected for the test based on cost, short delivery time, and compatibility of nozzle dimensions with existing burner guide pipes. The ARC-COAL CWSF was injected from opposite corners of the furnace at the top oil gun location. Combustion air preheat of 500 °F was used. The CWSF was slow in igniting, judging by the 6 to 8 ft distance between the nozzle and the point at which ignition occurred. This was due, in part, to the CE oil burner registers which were used unmodified. In spite of a borofuse coating applied for wear resistance, nozzle area had increased by more than 50 percent after 70 h of operation over 4 days. Coen subsequently revised its design, which has since demonstrated good durability. A total quantity of 2200 barrels (460 tons) of CWSF was used in this demonstration.

The South Carolina Electric and Gas Company conducted a lengthy test burn on Fluidcarbon CWSF at their Urquhart power station on Beech Island, SC, in 1985-86 (29, 30, 31, 32, 33, 34, 35, 36). The unit is a 75 MWe tangentially-fired pulverized-coal-burning CE boiler with three rows of four burners each, with each burner rated at 67 MBtu/h. Coen supplied four 30 MBtu/h, modified 2MV guns to replace one of the three levels of PC burners, the latter were left in place and the former were installed through existing observation ports. Unheated fuel was supplied at 50 to 60 psig while atomizing air was at 60 to 70 psig. Portions of the nozzles were protected with tungsten carbide and ceramic material. CWSF normally provided 10-15 percent of the heat input into the boiler but carried up to 40 percent of the load at times. Low atomizer wear was attributed to low slurry and air pressures, hence velocities. Over half a million gallons of CWSF were burned over 800 h of operation. After initial experience, 100 percent availability of the CWSF firing system was achieved.

A 6-hole Coen model CWA nozzle rated at 93 MBtu/h was used to fire Fluidcarbon CWSF in a front-fired industrial watertube boiler (29, 31, 33, 34, 35, 36). Rated at 76,500 lb/h of steam, the D-type, coal-designed, B&W unit is situated in a textile mill in Greenville, SC. The fuel pressure was below 100 psig, as was the pressure of the atomizing steam which replaced the compressed air used originally. Modifications to the boiler included extending the burner throat by 9 in. and relocating the windbox. Since no air preheating capabilities were available at the site, natural gas support was needed (averaged 3 to 8 percent over whole load range). Lightoff was on CWSF with 15 percent natural gas support. The boiler was operated successfully on CWSF 24 hours a day except for planned shutdowns on weekends. Fuel turndown of 5:1 was common. In all, over 350,000 gal of CWSF were fired over 2200 h of operation. However, the fuel supply contract between the textile mill and U.S. Fluidcarbon was cancelled after 8 months due to the drop in oil prices.

Five Coen burners rated at 50 MBtu/h each are being used in a retrofitted oil-designed utility boiler (Maritime Electric Co., Ltd.'s Unit No. 10) in Charlottetown, Prince Edward Island, Canada. The 20 MWe (190,000 lb/h of steam) oil-designed B&W two-drum, FD, pressurized Stirling-designed unit is front-wall fired with two rows of burners (33, 34, 37, 38). The lower three burners decline 5 degrees from the horizontal to increase residence time. Coen's twin-fluid steam-atomized burners exhibited no visible plume during testing and this was a major factor in their selection over three other candidates. Coen guarantees over 95 percent carbon conversion, and rates are typically over 98 percent for units in the 5 to 90 MBtu/h size range.

Peabody Engineering Company

Peabody's oil register burners have been successfully modified to burn various slurry fuels, i.e. coal-water, coal-oil, coal-methanol, and are available in the 10 to 300 MBtu/h size range (39, 40, 41, 42, 43). Peabody's oil-design, internal-mix, air-atomized, 6-hole nozzle does not correspond to either the Y-jet or T-jet types and is of intermediate complexity, as shown in Figures 43 and 44 (39, 40). At DOE's PETC, the nozzle has been used for the past several years (39, 40, 41, 42, 43) in conducting in-house combustion tests on several slurry fuels in a 100 hp firetube industrial boiler. Various nozzle materials were investigated at PETC, and end cap inserts made of tungsten carbide were found to exhibit a lower wear rate than other materials tested, i.e. hardened tool steel, low carbon steel, stainless steel (41). Typical conditions at the atomizer during testing at PETC are atomizing air pressure > 100 psig, fuel pressure < 100 psig, A/F < 0.5 (40). Another Peabody atomizer (model F14.1-0-75-F9 HZ), of somewhat different design and sized at 10 MBtu/h, was developed by the Ontario Research Foundation (44). It uses steam for atomization and is meant for use with COWMs. Wear characteristics were found to be much inferior to those of a modified, ceramic-protected Flosonic burner tip (44).

Hydro-Coal CWSF, prepared by the United Coal Company, was test-fired over a 2-week period in a package boiler designed for oil/natural gas firing at Valleydale Packers, Inc., of Bristol, VA (45). CWSF was fired through a Peabody atomizer that was modified on-site by PYRO Eng. Co. of Akron, OH. Fuel oil was fired through another nozzle located beside the CWSF nozzle. The existing Peabody PK-54 air register supplied with the boiler performed adequately. The modified Peabody atomizer was operated using air at 85 to 100 psig and performed well over several weeks. No serious erosion problems were encountered even though hardened steel was the only material of construction. The low operating pressures and small coal particle size were cited as the reason.

Peabody Holmes, Ltd. in England is affilitated with Peabody Engineering Corp. and has been more active than its U.S. branch in the area of CWSF combustion research and burner development. Details (46, 47, 48, 49, 50) and a summary (51) of the work performed are given elsewhere.

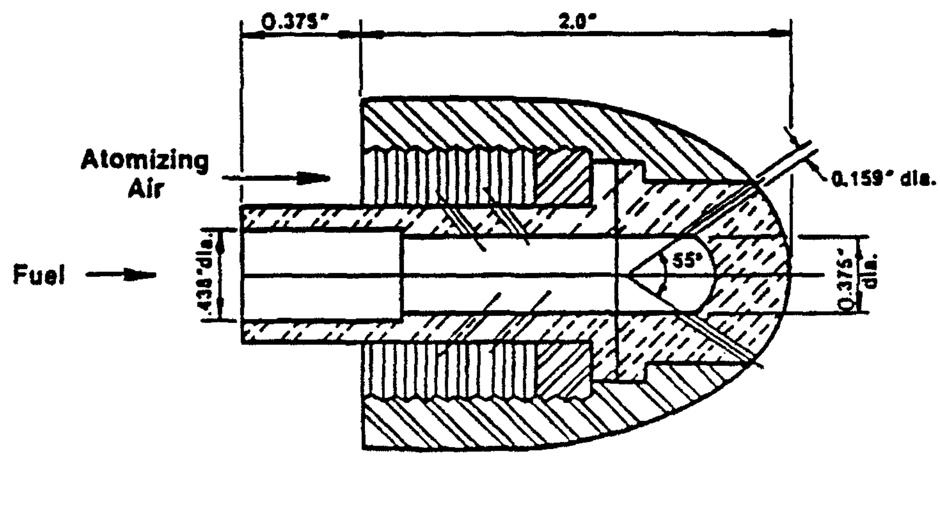


Figure 43. Peabody atomizer.

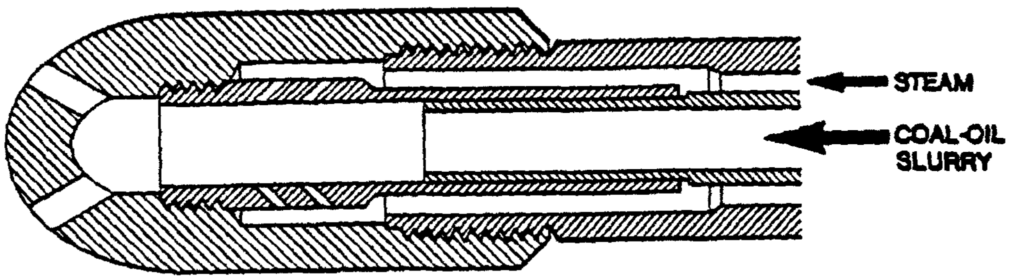


Figure 44. Peabody COM nozzle incorporating wear-resistant materials.

8 CONCLUSIONS

Based on the information gathered in this study, B&W and CE appear to have performed more work in the area of CWSF technology development and burner design and testing than the six other companies considered in this study. Over time, the performance data of B&W burners has improved to the point where they equal the EPRI performance targets in almost every category. Although the design has been modified, the burners are simpler to fabricate. CE has developed an aerodynamically sound burner that also meets almost all of the EPRI targets. The company continued development that resulted in a swirl-stabilized burner and an atomizer that resists erosion. Both companies have conducted CWSF development programs for both EPRI and DOE, and have received contracts from DOE on several aspects of CWSF technology.

The performance data indicate that B&W and CE burners should receive additional consideration and laboratory testing using realistic field conditions for use in the Army's central heat plants and package fire-tube boilers.

METRIC CONVERSION TABLE

1 Btu	=	1054.8 J
1 cP	=	0.001 Pa-s
1 ft	=	0.305 m
1 gal	=	3.785 l
1 hp	=	0.7457 kW
1 in.	=	25.4 mm
1 in. mercury	=	.04912 lb/sq in. (345 kg/m^2)
1 lb	=	0.453 kg
1 microns	=	0.000001 m
1 psi	=	178.6 gm/cm
1 ton	=	1016 kg
°C	=	0.55 (°F-32)

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NOMENCLATURE and ACRONYMS

A/F	atomizing medium to fuel mass flow rate ratio
AFT-SOHIO	Advanced Fuel Technology, a division of Standard Oil of Ohio (AFT was formerly a Gulf & Western Company)
ARC-COAL	the CWSF produced by the Atlantic Research Corp
ASTM	American Society for Testing and Materials
ATF	atomizer test facility
bbl/y	barrels per year
BCTU	basic combustion test unit
BET	Brunauer-Emmett-Teller
Btu/lb	British thermal units per pound
B&W	Babcock and Wilcox Co.
CBDC	Cape Breton Development Corp.
CAM	coal-aqueous mixture
CCA	close-coupled arch
CCS	close-coupled screen
CCWSF	conventional CWSF
CE	Combustion Engineering, Inc.
CIM	conical internal mix atomizer

CMU	Carnegie-Mellon University
CO	carbon monoxide
C/O	molar ratio of elemental carbon to oxygen
Co-Al	CWSF produced by the South Point, OH partnership that includes B&W
COM	coal oil mixture
COWF, COWM	coal oil water fuel, mixture
cP	centipoise, a unit of dynamic viscosity
CSC	critical solids concentration
CSG	coal-slurry-gas
CWSF	coal water slurry fuel (strictly speaking, if the word fuel is not included in the acronym, the material is not meant for direct firing); similar terms are: CWS, CWF, CWM, CLM, CAM, CLF, COM, PETCWF, PETCOM, and others where: M = mixture, L = liquid (any liquid including water, methanol, heavy fuel oil), A = aqueous, O = oil (usually HFO), PETC = petroleum coke.
DIPC	direct ignition of pulverized coal
DOE	Department of Energy
dsd	droplet size distribution
EPRI	Electric Power Research Institute
ESP	electrostatic precipitator
F/A	reciprocal A/F
FC	fixed carbon
FC/VM	fixed carbon to volatile matter ratio
FD	forced draft
FECO	Forney Engineering Co.
FEGT	furnace exit gas temperature
FPTF	fireside performance testing facility
FSBF	full-scale burner facility
FSI	free swelling index
ft/s, fps	feet per second
FW	Foster Wheeler Energy Corp.

gal/h, gph	gallons per hour
GJ/m^3	gigajoules per cubic meter
GJ/h	gigajoules per hour
gpm, gal/min	gallons per minute
HFO	heavy fuel oil
HHV	higher heating value (BTU/lb)
hp	horsepower
HSWF	high-swirl wall-fired (burner)
HVB	high volatile bituminous
ID	induced draft
KDL	Kreisinger Development Labs of CE, Inc.
KVS	Kennedy Van Saun Corp
lb/h	pounds per hour
LVB	low volatile bituminous
MB/h	mega (million) B per hour
MC	micronized coal
MCWSF	micronized coal water slurry fuel
METC	Morgantown Energy Technology Center
mm	millimeter
mmd	mass median diameter
mpe	maximum packing efficiency
MVB	medium volatile bituminous
MW	megawatts (if followed by: th, indicates thermal output of boiler; if followed by: e, indicates electrical output from generator)
NO	nitric oxide
NOx	oxides of nitrogen, includes nitric oxide and nitrogen peroxide, NO2
NSPS	new source performance standards
OXCE	CWSF production joint venture of Occidental Petroleum and Combustion Engg.

Pa	pascal, SI unit of pressure
PC	pulverized coal
PETC	Pittsburgh Energy Technology Center
PETCOM	petroleum-coke-oil mixture
PH	Parker Hannifin Corp.
ppm	parts per million (by weight)
psd	particle size distribution
psi	pounds (force) per square inch; in psia and psig, the a and g stand for absolute and gage, respectively
Δ Pwf	burner draft loss (the pressure drop from the burner windbox to the furnace)
REF	refractory chamber wall-fired (burner)
REF/REG	refractory/register (burner)
ROM	run of mine
RPM	rotations per minute
SA/V	surface area to volume ratio
$/kW	boiler conversion cost in dollars per kilowatt
$/MBtu	fuel cost in dollars per million Btu
smd	Sauter median diameter
SRC	solvent refined coal
SSBF	subscale burner facility
SSU	Saybolt Seconds Universal
TAN	tangential corner-fired (burner)
ton/d	tons per day
TGA	thermal gravimetric analysis
tph, ton/h	tons per hour
tons/yr	tons per year
UNDERC	University of North Dakota Energy Research Center
USEPA	United States Environmental Protection Agency

VIP	viscosity insensitive prefilmer
VM	volatile matter
vmd	volume median diameter

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